

NANCY - FRANCE



CHARTING THE PATH

TOWARD THE FUTURE

Geotechnical Engineering **Education**

JULY 2 - 4 2025

Proceedings of the 6th International Conference on Geotechnical Engineering Education: Charting the path toward the future, Nancy, France, July 2-4, 2025

Geotechnical Engineering Education 2025

Edited by

Michele Calvello, University of Salerno, Italy

Marina Pantazidou, National Technical University of Athens, Greece

Margarida Pinho-Lopes, University of Aveiro, Portugal



Proceedings of the 6th International Conference on Geotechnical Engineering Education:
Charting the path toward the future, Nancy, France, July 2-4, 2025

Geotechnical Engineering Education 2025

Edited by

Michele Calvello, University of Salerno, Italy

Marina Pantazidou, National Technical University of Athens, Greece

Margarida Pinho-Lopes, University of Aveiro, Portugal

ISBN: 978-618-84925-1-6 (Geotechnical Engineering Education 2025)

ISSN: 2732-7256 (Geotechnical Engineering Education)

Table of Contents

<i>Preface</i>	<i>vi</i>
<i>Organization</i>	<i>vii</i>
 <i>3rd John Burland Honor Lecture</i>	
Changing attitudes, organization and scale in engineering education: The teacher as a go-between and TC306 as a knowledge broker <i>M. Pantazidou</i>	3
 <i>Invited Papers</i>	
Undergraduate teaching of Unsaturated Soil Mechanics: building on fundamental physical mechanisms to pave the way for geotechnical analyses <i>A. Amabile & A. Tarantino</i>	23
Teaching numerical methods or teaching with numerical methods? <i>F. Ceccato</i>	43
What role should software play in geotechnical education? <i>N. Utter</i>	53
Geosynthetics in the classroom: Educating future engineers and their instructors <i>J.G. Zornberg</i>	63
 <i>Curricula: Undergraduate, (Post)Graduate, Doctoral</i>	
Game development-based learning curriculum module for undergraduate soil mechanics/geotechnical engineering classes <i>B. Ajmera, C. Rutherford, A. Poplin, A. Emery, J. Sabrowsky & P. Chung</i>	89
GEOMME project: an experience-based approach to teaching sustainable landslide hazard mitigation <i>V. Capobianco, G. Gilbert, L. Piciullo, T.H. Kwon, R. Nishii, N. Watanabe, J.Y. Park & M. Uzielli</i>	101
A 3-year multidisciplinary project training in Mining Engineering to build bridges across the disciplines <i>F. Descamps, N. Gonze, S. Vandycke, P. Ancia, T. Nikiema, O. Faÿ & J.P. Tshibangu</i>	113
Geotechnical engineering knowledge base needed for the improvement of mine tailings safety <i>B. Kovacevic Zelic, M. Burecic Safran & D. Znidarcic</i>	125
Simplifying slope stability: What should be taught at the undergraduate level? <i>C.J. MacRobert</i>	137
Developing parallel MSc / Degree Apprenticeship pathways in Geotechnical Engineering <i>A. Monzer, D.V.L. Hunt, I. Jefferson & A. Royal</i>	149
Two decades of evolution of study program on Geotechnical Engineering at the Faculty of Civil Engineering in Skopje <i>J. Br. Papić, J. Josifovski, I. Peševski, M. Jovanovski & M. Maraš</i>	161

Introducing geotechnical engineering discipline to K-12 STEM teachers for professional development <i>H. Seo & M. Yi</i>	169
An industry perspective on geotechnical engineering education and a learning approach by Tony Gee LLP <i>C.H. Shields, T.Y. Yap, C.T. Toms & T. Chalmers</i>	181
Linking theory to practice: the semantic wave in a postgraduate critical state soil mechanics course <i>T.S. da Silva Burke</i>	199
Teaching soil mechanics in a changing world <i>A.M. Tang, J.M. Pereira, F. Cuira & M. Vandamme</i>	211
 <i>Coursework: Laboratory, Field, Project-based, Numerical Methods</i>	
Running remote hands-on laboratory classes in soil mechanics <i>D. Airey & J. Zhu</i>	223
An international coursework on the design of a retaining structure and a building competition <i>V. Dimitriadi, D. Barreto, J. Leak, A. Arnold & H. Vogt</i>	235
Project-based learning on the design of retaining walls for geotechnical and civil engineering students <i>O. Jenck & D. Ricotier</i>	245
Using educational escape rooms in soil mechanics laboratory courses <i>K. Kluge, C. Budach & A. Kirsch</i>	257
The integration of environmental considerations into Geotechnical Engineering Education: Balancing optimization and sustainability <i>U.S. Okyay</i>	269
A design project on retaining wall design methods adopting comprehensive site investigation and laboratory testing <i>E. Theron, J.D. Steenkamp, S.G. Waters & P. Vosloo</i>	281
 <i>Open Resource Educational Material</i>	
Development of shareable activity library for geoenvironmental engineering education <i>G. Bohnhoff, K. Sample-Lord, J. Hubler, N. Strandberg & J. Walleiser</i>	293
Open Educational Resources for geotechnical engineering education <i>W. Fellin</i>	303
Settlement calculations of a motorway embankment and comparison with field measurements: An education case study <i>V. Xenaki & M. Pantazidou</i>	315
 <i>Applications of ICT Tools</i>	
Enhancing geotechnical site investigation and project-based education through virtual reality: the GeoSim experience <i>A. Abdallah, O. Cuisinier & F. Masroui</i>	329
Implementation of a blended learning strategy for geotechnical courses <i>L. Araújo Santos, V. Ribeiro & S. Proença</i>	339

Use of virtual reality for teaching geotechnics – application to the study of an abandoned underground mine

O. Deck 351

Faculty perceptions and usage of generative AI in geotechnical engineering education

E. Salifu, A. Cuccurullo & S. Muguda 361

PEGGHY - Platform for Experimental Geophysics, Geotechnics and Hydrogeology of the Graduate School of Geological Engineering, Nancy, France

J. Sausse, P. Cupillard, A. Abdallah, Y. Géraud, M. Diraison, C. Oltean, F. Golfier & O. Cuisinier 371

Links to Research on Learning and on Engineering Education

Teaching soil mechanics core concepts: mapping the structure of university textbooks worldwide

M. Calvello 387

Developing concept inventories for Geotechnical Engineering

A. Kirsch, W. Fellin & R. Sonnenberg 401

Enhancing student learning in geotechnical engineering: a study on effective slide design from students' perspective

V. Mangraviti, L. Brezzi, G. Dalla Santa, F. Gabrieli & F. Ceccato 415

Priority Theme 1: Teaching of Unsaturated Soils

Integrating soil suction in geotechnical education: a case study on partially saturated slope stability analysis in Sweden

A. Abed & M. Karstunen 429

Why unsaturated soil mechanics is relevant to civil engineers

K.V. Bicalho 439

Including unsaturated soil concepts in undergraduate courses: The UPC experience

A. Ledesma, E. Romero, P.C. Prat, A. Ramon & N.M. Pinyol 447

Teaching unsaturated seepage and wetting-collapse coupled modelling

N.M. Pinyol & E.E. Alonso 459

Teaching unsaturated soil mechanics in a South African context

T.S. da Silva Burke & C.J. MacRobert 471

Teaching unsaturated soil mechanics through rammed earth

C. Vulpe & C.T.S. Beckett 483

Priority Theme 2: Use of Numerical Modeling to Support Teaching

Short-term versus long-term stability problems in clay explained through classical figures and finite element simulations

M. Matos Fernandes, J.L. Borges & M. Pantazidou 495

Integrating advanced computational tools into geotechnical engineering education: an example of transformative learning through digital technology

H. Moghaddasi, M. Moradi, A. Tarantino & B. Ogwezi 507

The role of numerical modelling within a pedagogical framework for soil mechanics courses: implementation for stresses in soils <i>M. Pinho-Lopes & J. Macedo</i>	519
Steady-state groundwater flow - combining physical models, hand-drawing and numerical solutions to study plane flownets <i>M. Pinho-Lopes & W. Powrie</i>	533
Applied numerical analysis in Geotechnical Engineering: a Masters module from the perspectives of the academic, teaching assistant and students <i>A. Tsiampousi & P. Tantivangphaisal</i>	547
Initial study on leveraging digital tools for geotechnical education: enhancing practical training with databases at CiviLab@CUT <i>S.G. Waters & E. Theron</i>	559
Teaching the significance of numerical model validation with problem-based learning: examples from rock mechanics <i>P. Yiouta-Mitra</i>	571
<i>Author Index</i>	583

Preface

The international conferences on Geotechnical Engineering Education (GEE) are organized by the technical committee TC306 of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). Geotechnical Engineering Education 2025 (GEE 2025) was organized under the auspices of the French Soil Mechanics Committee (CFMS) and the University of Lorraine, with support by academic and professional French organizations and major French geotechnical engineering companies, and chaired by Professor Farimah Masrouri of Université de Lorraine.

In addition to the recurrent education theme topics in GEE conferences, namely, *Curricula*, *Coursework*, *Open Resource Educational Material*, *Applications of ICT Tools* and *Links to Research on Learning and on Engineering Education*, GEE 2025 had two priority themes: *Teaching of Unsaturated Soils* (Priority Theme 1) and *Use of Numerical Modeling to Support Teaching* (Priority Theme 2). Sessions on priority themes were complemented by invited thematic presentations, fostering a lively exchange of ideas.

These proceedings are primarily a record of what the conference leaves behind. They cannot, however, convey the camaraderie that animated the event. Many attendees savored for the first time the rare luxury of dedicating two uninterrupted days to focused discussion of geotechnical engineering education — an opportunity made possible by the collegially masterful GEE 2025 hosts and the insightful authors whose contributions are collected here.

Michele Calvello
Marina Pantazidou
Margarida Pinho-Lopes
September 2025

Organization

GEE 2025 Organizing Committee

Chair: Farimah Masrouri, Université de Lorraine, France

Members:

Adel Abdallah, Université de Lorraine, France

Nicolas Chabrat, Université de Lorraine, France

Olivier Cuisinier, Université de Lorraine, France

Olivier Deck, Université de Lorraine, France

Philippe Gotteland, FNTF, France

Mahdia Hattab, Université de Lorraine, France

Orianne Jenck, Institut National Polytechnique de Grenoble, France

Rasool Mehdizadeh, Université de Lorraine, France

Sandrine Rosin, Université de Lorraine, France

GEE 2025 Program Committee

Marina Pantazidou, National Technical University of Athens, Greece (coordinator)

Gretchen Bohnhoff, University of Wisconsin at Platteville, USA

Michele Calvello, University of Salerno, Italy

Andy Leung, Hong Kong Polytechnic University, Hong Kong

Charles MacRobert, Stellenbosch University, South Africa

Farimah Masrouri, Lorraine University, France

Silvana Montoya-Noguera, Universidad EAFIT, Colombia

Margarida Pinho-Lopes, University of Aveiro, Portugal

GEE 2025 Scientific Committee

Asif Ahmed, SUNY Polytechnic Institute, USA

George Anoyatis, KU Leuven, Belgium

David Airey, University of Sydney, Australia

John Atkinson, City University, UK

Katia Bicalho, Federal University of Espírito Santo, Brazil

Giovanna Biscontin, National Science Foundation, USA (UK)

Gretchen Bohnhoff, University of Wisconsin at Platteville, USA

Susan Burns, Georgia Institute of Technology, USA

Brian Byrne, IT Carlow, Ireland

Michele Calvello, University of Salerno, Italy

Francesca Ceccato, University of Padua, Italy

Ilhan Chang, Ajou University, South Korea

Liang Cui, Lakehead University, Canada

Vasiliki Dimitriadi, Edinburgh Napier University, UK (Greece)

Silvina Echazú Lamas, Universidad Nacional de Salta, Argentina

Tugba Eskişar Tefçi, Ege University, Turkey

George Fanourakis, University of Johannesburg, South Africa

Margarida Fernandes de Pinho Lopes, University of Aveiro, Portugal

Ana Heitor, University of Leeds, UK

Mark Jaksa, University of Adelaide, Australia

Orianne Jenck, Grenoble Alpes University, France
Polixeni Kallioglou, University of Thessaly, Greece
Mamoru Kikumoto, Yokohama National University, Japan
Emil Mejlhede Kinslev, Technical University of Denmark, Denmark
Biljana Kovačević Zelić, University of Zagreb, Croatia
Tae-Hyuk Kwon, Korea Advanced Institute of Science and Technology, South Korea
Robert Lanzafame, TU Delft, The Netherlands
Alberto Ledesma, Polytechnic University of Catalonia, Spain
Andy Leung, Hong Kong Polytechnic University, Hong Kong
Xia Li, Southeast University, China
Huabei Liu, Huazhong University of Science and Technology, China
Charles MacRobert, Stellenbosch University, South Africa
Francisco Javier Manzano Diosdado, Cádiz University, Spain
Farimah Masrouri, Lorraine University, France
Manuel Matos Fernandes, University of Porto, Portugal
Bryan McCabe, National University of Ireland Galway, Ireland
Toshifumi Mukunoki, Kumamoto University, Japan
Silvana Montoya-Noguera, Universidad EAFIT, Colombia
Hideki Ohta, Chuo University, Japan
Rolando Orense, University of Auckland, New Zealand
Anitha G. Pillai, SCMS School of Engineering & Technology, India
Marina Pantazidou, National Technical University of Athens, Greece
Muhsin Rahhal, University of Saint-Joseph, Lebanon
Anna Ramón Tarragona, Polytechnic University of Catalonia, Spain
M. Rama Rao, JNT University, Kakinada, India
Saibaba Reddy, JNT University Hyderabad, India
Rodrigo Salgado, Purdue University, USA
Klaas Siderius, Fugro Geoservices, The Netherlands
Francisco Javier Torrijo, Universitat Politècnica de València, Spain
Roberto Vassallo, University of Basilicata, Italy
Vasiliki Xenaki, Edafomichaniki SA, Greece
Jun Yang, University of Hong Kong, Hong Kong
Fayrouz Yasser, Mansoura University, Egypt

3rd John Burland Honor Lecture

Changing attitudes, organization and scale in engineering education: The teacher as a go-between and TC306 as a knowledge broker

M. Pantazidou

National Technical University of Athens, Zografou, Greece
mpanta@central.ntua.gr

ABSTRACT: This paper campaigns for the production of targeted teaching materials for engineering education, proposes a framework for their production, and describes example applications in geotechnical engineering. The perspective of the paper is content-based and calls for two fundamental changes in attitude. First, shedding the assumption that geotechnical engineering instructors have ample suitable teaching materials to choose from. Second, adopting in education the practice of peer review. For organizing the production of teaching materials, the literature of education offers the framework of pedagogical content knowledge. Pedagogical knowledge of content focuses on how content is perceived by both instructors and students and on how to guide understanding of content towards generative perceptions and away from misinterpretations. The paper describes the use of this framework to develop small-scale open teaching material for soil compaction. Developing teaching materials and peer review take significant time; without the incentives of research, it can be done by reducing the scale of the undertaking and of the personal involvement. Some progress has already been made by TC306, the technical committee on geo-engineering education. Collectively, the advocated changes transform the teacher into a go-between who bridges experience levels and connects ideas. By fostering collaboration, TC306 acts as a knowledge broker.

Keywords: Educational materials, Peer review in education, Pedagogical content knowledge, Soil compaction

1 Introduction – Engineering education and its tools, educational materials

This paper sets forth priority changes with the potential to accelerate the improvement of undergraduate geotechnical engineering education. The changes have direct impact on teaching materials, the basic tools of an instructor, while the development of teaching materials can act as a catalyst for some of the advocated changes. This article is a hybrid of technical paper, case study and opinion paper. It is an opinion paper, since prioritization has a subjective element. It is a technical paper on education, since advocated changes are grounded in the literature of education. It is also a case study, since the advocated changes are exemplified with small-scale open teaching material for the topic of soil compaction. As a paper accompanying the third John Burland Honor Lecture, it continues the tradition of the previous two Burland lectures (Atkinson, 2016; Jaksa, 2020) of focusing on content and content-related outcomes of undergraduate instruction in geotechnical engineering and adds emphasis on content of teaching materials. What is more, it brings perspectives from the literature on education from a content-based point of view. The ultimate aim of the paper is twofold: expand the traditional role of the teachers, by painting a picture of them acting as go-betweens for people and ideas, and add the role of a knowledge broker to the customary function of a technical committee as knowledge hub. Since the paper combines topics from engineering education and geotechnical engineering, it can be read selectively as follows. Readers with interest in education without geotechnical engineering background may read Sections 2-5, 8, which present the evidence-based advocated changes, and the conclusions, whereas geotechnical engineering instructors with little available time may focus on Sections 5-7, which present the development of teaching material for soil compaction.

2 Educational materials include teaching and learning materials

Educational materials, or course materials, accompany teaching and can be used independently by learners. Educational materials are specifically designed and produced to be used in instruction or can be used in instruction with minimal adaptation. They include textbooks in printed or electronic format, published papers, online material, such as videos of any kind, and educational software of any kind, including education versions of commercial software (adapted from Skoumios & Skoumpourdi, 2018). Despite the more recent additions of online materials, the popularity of textbooks holds. When the printed and the electronic format coexist, they are equally popular (Moore, 2024). Ostensibly written for students, textbooks are perhaps more indispensable for teachers (see also Section 6.2.2).

As discussed by Pantazidou and Calvello (2024), educational material is a common research topic in the education literature for lower levels of education, since it is anticipated that teachers may have some knowledge gaps (Davis et al., 2016). In contrast, the high content expertise of university instructors often leads to the assumption –questioned by Pantazidou and Calvello (2024)– that this literature is irrelevant to tertiary education. However, since teaching at all levels has some common elements, even the literature for primary-secondary education can yield some useful overarching guidelines for desired educational material. For instance, teachers value materials that support their own learning, not just that of their students. (Ball & Cohen, 1996). More recently, Calvello (2025) conducted a survey on textbooks suitable for introductory courses in soil mechanics and geotechnical engineering; hence, a long and varied list of introductory textbooks is readily available for a study of what is covered and what might be missing.

The term “teaching materials” is used herein for materials developed primarily –or even solely– for the needs of the teacher. By the same token, “learning materials” can refer to materials created primarily for the needs of the student. By separating the two groups, we may be able to serve more effectively their different needs. In other words, teaching materials can be meant only for the teacher’s preparation, written for the teacher’s level, without worrying that students may be confused. The teacher acts as a facilitator, connecting students with the teaching materials and helping them derive meaning from the content. At the same time, peer guidance in the form of clear, manual-style instructions can help teachers understand the purpose and use of the materials, saving time that might otherwise be spent evaluating unsuitable content. Guidance to the teacher is a rarely discussed necessity; currently, the terms reusable, transferable or shareable educational material denote more the intent rather than the end result. Making such material available with open licensing (Creative Commons – CC licenses) is part of the broader discussion (Fellin, 2025), but beyond the scope of this paper.

3 Changes in perceptions and therefore attitudes

This section discusses two common unexamined perceptions, with the objective to effect corresponding changes of attitudes. The first perception concerns the hypothesized abundance of educational materials for engineering instruction. The second perception concerns the available tools to evaluate the quality of educational materials, i.e. their usefulness.

3.1 Do we have the educational materials we want?

Pantazidou and Calvello (2024) ran an online survey to find out (i) whether geotechnical engineering instructors have available a variety of satisfactory educational materials and (ii) the types of educational material they desire. The questionnaire was first sent to the members of TC306, the technical committee on geo-engineering education of the International Society for Soil Mechanics and Geotechnical Education (ISSMGE). Then it was made available to the wider geotechnical community after being disseminated through ISSMGE media and events. From the 94 responses received, 63 responses met criteria of “completion with diligence” and were included in data analysis. To the question: “Are you satisfied with the educational material you currently use in your teaching?” 52% of the instructors replied that they are not adequately satisfied. To the question “Were you satisfied with any material found after searching?” 45% of the instructors replied negatively. These sizable percentages establish that there is room for improvement and disprove the –evidently unexamined– abundance assumption, i.e. that in the internet era instructors have available for their lectures a variety of satisfactory educational materials to choose from.

3.2 Peer review & student evaluations: we want them both

The proverbial Martian scientist would be surprised at the absence of peer review in education, given its ubiquity in research. Since more or less the same people engage in both at university level, why haven't the benefits of peer review attracted the attention of university educators? Herein it is hypothesized that at least part of the explanation is the perception that educators have an alternative tool: student evaluations. Perhaps the relative ease of obtaining student evaluations has made them the unquestioned "quality assessment" standard to the point that we rarely ask what student evaluations actually measure.

Students are clearly the best source to find out about their perceptions of learning and in particular how they experience the process of learning themselves. However, in terms of learning outcomes, student responses should be interpreted in the context of the relevant literature, which shows that self-assessment is not correlated with respondents' performance (Ambrose et al., 2010), particularly in the low-performance domain (Kruger & Dunning, 1999). More revealing are studies with students' responses to questions about the process and outcomes of learning in engineering topics, which are complemented by independent assessment of the learning outcomes. Yadav et al. (2010) studied the effectiveness of using a mechanical engineering case study as a teaching tool compared to a lecture. They used independent tests to measure the performance of students, who were also asked whether the case or lecture helped them in their learning. While the tests showed that indeed the use of the case study resulted in greater learning gains, more students responded that the lecture helped their learning (probably because the lecture is a more familiar teaching medium). In a more recent study, Yadav et al. (2019) used two case studies for two course topics (hydraulic systems and electro-mechanical systems). Participants were asked to complete a quiz, for the assessment of their learning, and a survey, with questions about their perceptions of learning and engagement. Results suggested that students' perceptions about their own learning did not predict their actual learning outcomes while their perceptions of engagement predicted their conceptual understanding. Deslauriers et al. (2019) report similar findings in a paper contrasting "actual learning" versus the "feeling of learning" of students in large-enrollment introductory college physics courses. Deslauriers et al. (2019) note that this discrepancy suggests that attempts to evaluate instruction based on students' perceptions of learning could inadvertently promote inferior pedagogical methods. Perhaps we should not go that far, and definitely we should continue monitoring students' perceptions. At the same time, these results might make us rethink the place of peer review in education. In fact, producing educational materials may offer an ideal gateway for introducing peer review into education; for examples, see Bohnhoff et al. (2025). Given that teaching materials, as defined herein, are meant for instructors, they are prime candidates for peer review.

4 Changes in the organization of content

If the available educational materials do not meet all instructors' needs, producing more of the same is unlikely to help. To this end, this section discusses two complementary ways to approach content that may suit more varied teaching needs.

4.1 Pedagogical content knowledge: A framework for the production of teaching materials

Shulman (1986) was the first to recognize the new knowledge brought about by teaching experience as a distinct field of knowledge, which he called pedagogical content knowledge, now also known in the literature of Education by its acronym, PCK. (Acronymification is often undesirable, as we may forget what the acronym stands for.) In essence, Shulman (1986) argued for the necessity to build a supplementary body of knowledge for every domain X: the pedagogical knowledge of X. Herein, "pedagogical content knowledge" refers to the broader framework, and "pedagogical knowledge of X" refers to a specific domain or topic. To place this new knowledge in context, it is useful to distinguish between (I) domain-specific and, hence, content-specific and (II) domain-general knowledge for teaching X, as shown in Figure 1. In this framework, pedagogical knowledge of X (Ib) is one of the three content-related components of the knowledge of the instructor, in addition to the subject matter knowledge of X (Ia) and the curricular knowledge of X, i.e. of available educational materials (Ic). Figure 1 facilitates distinctions between (Ia) knowledge of X (e.g. of a geotechnical engineering researcher or

practitioner) and (Ib) pedagogical knowledge of X (e.g. of a geotechnical engineering instructor), as well as between (Ib) pedagogical knowledge of X (which is domain-specific) and (II) pedagogical knowledge for teaching (which is domain-general, e.g. it includes generic teaching tips).

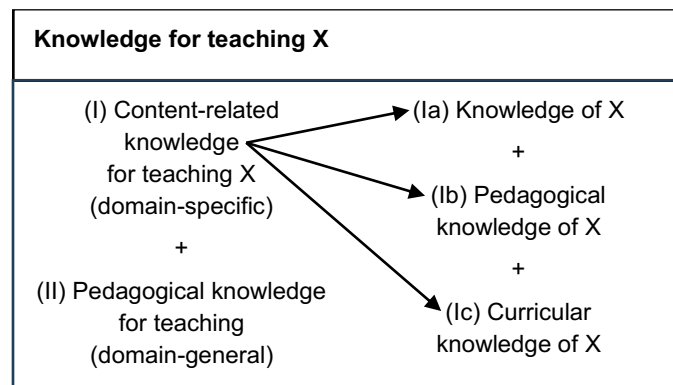


Figure 1. Distinguishing (I) content-related knowledge for teaching X and (II) pedagogical knowledge for teaching: pedagogical knowledge of X (Ib) is one of the three components of the content-related knowledge of an instructor in domain X.

Shulman (1986) summarized the constituent elements of pedagogical content knowledge as “knowledge of the ways of representing and formulating the subject that make it comprehensible to others” and included, for the most regularly taught topics in one’s subject area, “the most powerful analogies, illustrations, examples, explanations and demonstrations”. In brief, pedagogical knowledge of X is all about explaining for understanding. Shulman also included in this knowledge “an understanding of what makes the learning of specific topics easy or difficult”, as well as students’ misconceptions, i.e. what might stand in the way of understanding. As described by Shulman, pedagogical content knowledge offers a framework to approach educational materials with an emphasis on making content approachable and taking into account students’ difficulties. Given that explanations and illustrations are central to textbook writing, this study hypothesized that pedagogical content knowledge –though not explicitly present in textbooks– may emerge through a comparative analysis of multiple textbooks. This is attempted in Section 6.2.2 for the topic of soil compaction.

4.2 Big ideas and key concepts to concentrate production efforts

This section adds to the framework of pedagogical content knowledge complementary ways to approach “the most regularly taught topics” mentioned by Shulman (1986). Wiggins and McTighe (2005) recommend that instructors organize units of instruction around the “big ideas” a course aims to develop. According to them, the term “big idea” represents “a concept, theme or issue that gives meaning to discrete facts and skills”. Big ideas are big only within the domain, i.e. not universally. In this context, big ideas are the major threads that run horizontally through chapters of single-discipline textbooks. They are akin to the organizing principles used by experts in arranging domain knowledge. Or, again in the words of Wiggins and McTighe (2005), “they are the hard-won results of inquiry, ways of thinking and perceiving that are the province of the expert”. The existence of foundational key concepts in disciplines is a more mainstream idea. In education research, they are the basis for developing concept inventories for engineering disciplines, including geotechnical engineering (Kirsch et al., 2025). While formulas yield numerical answers to assignment problems, concepts help us organize better our thinking to make sense of the numbers we obtain. To sum up, Section 4 suggests we develop educational materials within the framework of pedagogical content knowledge, i.e. we keep in mind its constituent elements, ideally for topics that highlight key concepts and offer views, or even glimpses, of big ideas. An example is included in Section 7 for the topic of soil compaction.

5 Choice of topic for developing teaching material for soil compaction and introduction for the non-specialist

The topic of soil compaction was chosen to give examples of the ideas presented in Section 4 through the development of small-scale open teaching material. The background of the development is presented in Section 6 and its products are included in Section 7 and the Online Supplement. Compaction is a good candidate for studying its pedagogical knowledge because it is a topic free of any serious technical disagreement within the geotechnical engineering community, to the author's knowledge. Perhaps it appears as a less than ideal candidate because some introductory textbooks in geotechnical engineering cover soil compaction while others do not; what is more, the place of soil compaction in the contents also varies (Calvillo, 2025). The author has conducted a limited survey using the 10-12 textbooks she regularly consults on topics taught in introductory soil mechanics courses. In these textbooks, soil compaction is an early chapter, right after soil description and classification, or is included in a later section on applications, e.g. soil improvement, or with unsaturated soils (see Table S1 in Online Supplement). This variety appears promising, since, as already mentioned, pedagogical knowledge of content is expected to be scattered in textbooks. To textbooks we will return then, in Sections 6.2.2 and 6.2.3, after introducing in the remainder of this section the basics of soil compaction in a manner friendly to the non-geotechnical engineer.

Soil compaction is a form of soil improvement. It accomplishes densification of soil using mechanical energy to reduce the volume of air in the space between soil particles, known as soil pores. In the field, mechanical energy is imparted using a variety of specialty rollers. Although in-place soil can be compacted to some limited depth, soil compaction is typically done on excavated soil (Lambe & Whitman, 1979). Common applications of "building with soil" include constructing an embankment (for a road or an earth dam), placing soil behind a retaining wall to form a terrace and filling a trench (Powrie, 2014).

Compaction of soil is facilitated with the addition of water. The theory of soil compaction draws evidence from laboratory studies on compacted soil samples. When visualizing any soil sample, the most fundamental consideration is that soil is made up of solid particles, which we will call "solids", and the soil pores, which we will call "pores". The next step is to visualize that pores contain:

- both air and water in the general case,
- only air when the soil is completely dry (a rarity in the field but a common laboratory artifact), or
- only water (typically below the level where water rises in wells in the field), in which case we say that the soil is saturated.

In other words, soil mechanics deals with a multiphase material, considering soil's three phases in the general case, i.e. solids, water and air.

The degree of soil densification achieved depends on the amount of water in the soil and the factors that affect this relationship, i.e. soil type and the energy applied. The densification of soil when compacted is studied with laboratory tests imparting a standardized amount of energy (a standard weight falling from a specified height for a specified number of repetitions) on moist soil placed in a standardized compaction mold. Figure 2 depicts the basic features of the relationship obtained experimentally between water content, w (mass of water/mass of solids) on the x-axis, and a measure of how dense or compact soil is on the y-axis. The most easily computed measure from laboratory compaction tests is the dry density of soil, ρ_d (kg/m^3) (mass of solids/soil volume = mold volume), which can then be converted to dry unit weight, γ_d (kN/m^3), which was chosen for Figure 2, because it is the more common parameter used in soil mechanics. The non-specialist, and the student as well, may be confused by a test performed with moist soil, the results of which are then expressed as if the soil were dry. Hence, it is worth clarifying that ρ_d and γ_d characterize the same soil being compacted, but in a hypothetical state of zero water content. Disregarding thus water places emphasis on the soil particles, which carry the loads imposed on soil. Accordingly, we choose a parameter that accounts only for the soil particles, since the role of water in compaction is ancillary, i.e. only to help obtain a denser soil. Figure 2 includes two curves depicting the relationship between water content and dry unit weight for two compaction levels: high and low imparted mechanical energy, also known as compactive energy. As shown in Figure 2, each curve is drawn with the help of six tests at different water contents (the dots on the curves). The peak of each compaction curve corresponds to the maximum dry unit weight, $\gamma_{d\text{max}}$, i.e. the optimum compaction for the specific energy level, which is achievable for the respective optimum water content,

w_{opt} . Graphs of compaction curves often include also the “zero air voids” line, which gives the computed relationship between dry unit weight and water content at degree of saturation (volume of water/volume of pores) equal to 100%. This line gives, for each value of water content, the theoretical upper bound for the dry unit weight of the soil if it were possible to compress the soil pores in a way to selectively eliminate all air while leaving the existing water, i.e. for a degree of saturation of 100%. (The zero air voids line may be doubly confusing to conceptualize, since it refers to the hypothetical dry soil corresponding to an imaginary saturated soil.) In order to compute pairs of water content, w , – dry unit weight, γ_d , on the zero air voids line, we assume a value for the specific density of the soil particles, G_s (density of solids/density of water), typically between 2.65 and 2.75. Similar lines can be determined for any amount of air voids and the corresponding degree of saturation; Figure 2 includes a second line for 80% degree of saturation. When the same soil is compacted in the field with a roller imparting equivalent compactive energy, the laboratory results provide guidance for the field compaction specifications, which typically designate a range of water content around w_{opt} that is expected to give a γ_d close to γ_{dmax} , e.g. 90% or 95% of γ_{dmax} (see also Section 7.1.2).

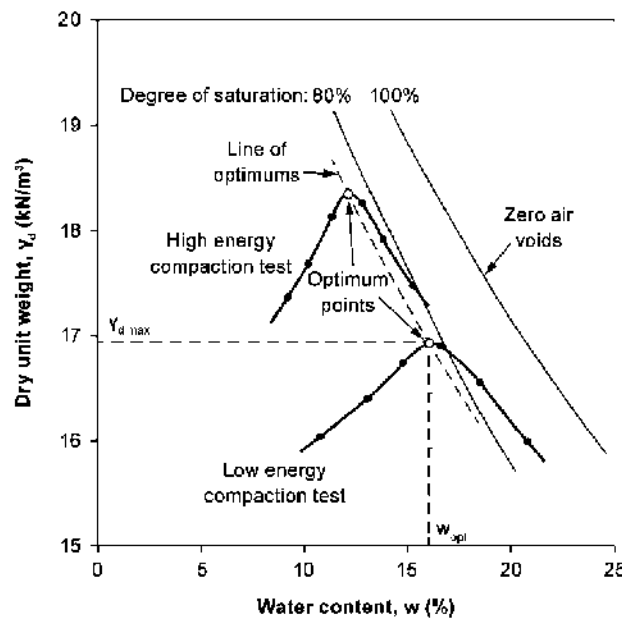


Figure 2. Two compaction curves obtained experimentally using high (top curve) and low (bottom curve) compactive energy and two computed lines of constant degree of saturation, 80% and 100% (i.e. zero air voids). The constant degree of saturation lines were computed for specific density, $G_s = 2.70$. Graph modified from Fredlund and Rahardjo (1993).

6 Instructional decisions vs pedagogical decisions within the framework of pedagogical knowledge of soil compaction

6.1 Content & instructional decisions: teaching or not teaching soil compaction

With a background similar to that presented in Section 5 and the details provided by the assigned textbook, the instructor is called to decide whether to include or not compaction in an introductory soil mechanics course. This is an instructional decision, and it is not foregone. Not all introductory soil mechanics textbooks cover soil compaction, as already mentioned, a clear sign that, despite the ubiquity of its applications, compaction is a topic that can be omitted. Several textbooks that cover compaction do so early on. As presented in Section 5, the basics of compaction are mostly descriptive, hence relatively easy to grasp. In addition, they offer opportunities for practicing computations with key soil parameters covered in all introductory courses and all introductory textbooks, including the dry density, the dry unit weight and the water content. Students can be given laboratory measurements, typically of five to six compaction tests performed at different water contents, and construct on their own the compaction curve depicted in Figure 2. In fact, the presentation of soil compaction in some textbooks gives the impression that the main goal of teaching compaction is to train students to conduct such

laboratory experiments themselves and record their results. If this is indeed the only approach to teach soil compaction, the instructor may be tempted to skip it and save the time for a more challenging topic.

6.2 Content & pedagogical decisions: considering learning opportunities afforded by soil compaction and potential difficulties

Let's now assume that the decision to teach compaction is already made for us, but how to teach it is up to us. The answers to this "how" can be given by pedagogical decisions, i.e. how to teach will be guided by the learning opportunities afforded by soil compaction, as these opportunities are perceived by the instructor, i.e. according to his/her pedagogical knowledge of compaction.

As already mentioned, the approach selected herein was to first glean from textbooks the pedagogical knowledge of compaction. This side-by-side study of several textbooks produced instances of useful variations (Section 6.2.2) and some more unanticipated observations, sometimes problematic (Section 6.2.3). To appreciate better these variations, the reader will first be reminded in Section 6.2.1 of the additional parameters that describe relationships between the three soil phases. This time, we will consider each one from a pedagogical point of view, i.e. consider how students may perceive them, with emphasis on potential difficulties.

6.2.1 Alternative parameters to describe soil compaction

The two parameters discussed so far that express, in different ways, how much water is contained in the soil are the water content, w (mass of water/mass of solids), and the degree of saturation, S (volume of water/volume of pores). The denominator of water content is constant. As water is added sequentially for each compaction test, the mass of the added water can readily be determined from the known added volume of water to compute the new nominator. This attractive practical convenience of using water content is counterbalanced –from a pedagogical point of view– by its low information value as to the actual quantity of water in the soil pores. To complete the picture, we also need the degree of saturation, S . From a cognitive point of view, the degree of saturation is an easier quantity to make sense of, since it expresses *part of a whole* (the part of pore volume filled with water) and, hence, is bounded between 0 and 1, or 0% and 100%. In contrast, the water content expresses the *proportion* of two quantities and, on its own, does not provide adequate information on the state of the soil, especially if the soil is moist (unsaturated).

Regarding alternative measures of how dense the soil is, in addition to the two already mentioned, i.e. the dry density, ρ_d , and the dry unit weight, γ_d , which express a similar idea, there are three more. A cognitively appealing parameter is porosity, n (volume of pores/volume of soil), which –similar to the degree of saturation– expresses part of a whole. Porosity is bounded between 0 (an impossible value, corresponding to a perfectly solid rock) and 1 (also an impossible value corresponding to air or water). As the soil becomes denser, both the nominator and the denominator of porosity decrease, and this is its drawback from a computation point a view. In contrast, void ratio, e (volume of pores)/(volume of solids), has a constant denominator (similar to the water content, w). Because of this computation convenience, the void ratio is used often in soil mechanics. As a relative proportion, void ratio has no natural upper bounding value. For clayey soils, which can have a more open structure relatively to sandy soils, void ratio can be higher than 1. This is often confusing to students, who if they compute $e > 1$ think they made a mistake. A final cognitive-linguistic drawback of void ratio is that the word "void" connotes empty pore space, which is problematic when pores contain water. It is relevant to stress here that for other civil engineering disciplines that deal with water in soils, e.g. near-surface hydrology, groundwater hydrology, contaminant transport in groundwater, porosity is the only quantity of interest. This is because in these disciplines the deformation of soil (e.g. any volume changes) is rarely relevant. Lastly, theoretical soil mechanics, specifically the critical state theory, uses specific volume, v (volume of soil/volume of solids), which expresses how much total volume is occupied by a certain volume of soil particles, i.e. another proportional quantity. The use of specific volume, v , which by its definition is equal to one plus void ratio, $1 + e$, is consistent to the foundational feature of the critical state theory to account for the behavior of soil through its tendency to either contract (volume reduction) or dilate (volume increase), critical being the state when the soil deforms under constant volume, an eventual state all soils tend to when they undergo intensive shear deformation. (Note that "critical" is another unfortunate choice of term, because nothing is "about to change" at the critical state; on the contrary, the soil volume

ceases to change.) Hence, compaction may serve as an effective starting point for introducing students to specific volume, v , a parameter that will prove essential in later topics of critical state soil mechanics.

6.2.2 Textbooks: variations of pedagogical knowledge of soil compaction

The overall question asked herein was which textbooks enrich the “homogenized” version of soil compaction presented in Section 5. Table S1 in the Online Supplement lists the surveyed 10 textbooks and one specialty book on compaction; it includes brief comments and is accompanied by an annotated list of the 11 references with paragraph-long comments and key excerpts (see Text S1 in the Online Supplement). Selected specific questions and answers found in these books are discussed next.

How do different textbooks treat alternative parameters used for the compaction curve?

Taylor’s (1948) version of Figure 2 (Fig. 18.2) includes three measures of density, with three y-axes for dry unit weight, porosity and void ratio, showing thus clearly that they are interchangeable. In the same figure, Taylor also chose to show the (moist) unit weight, likely in recognition of the cognitive dissonance mentioned in Section 5 (performing compaction tests with moist soil but plotting results for the equivalent in-terms-of-density dry soil). The definition given for dry unit weight (weight of the solids per unit of volume of soil in the compacted state) and the term used for it (*unit dry weight*: implying that the *weight* is dry, not the soil) may be more friendly to the learner.

Powrie (2014), following Bolton (1979), has a compaction plot (Fig. 1.19b) that shows the relationship between specific volume, v , as the primary density measure, and water content, w , and also includes several constant saturation lines, which are straight lines for a set of v - w axes [same as in the e - w axes used by Bolton, (1979)]. Showing several constant saturation lines (i.e. not only the zero air voids line, or at most 2-3 lines of constant degree of saturation) helps the reader perceive the initial rapid increase in saturation until the optimum point is reached and its minimal increase past the optimum point. This very useful figure is included with permission in the Online Supplement (Figure S2).

What do we learn from alternative graphs in different textbooks?

Because of the empirical nature of compaction theory, effectively conveying its key concepts depends on tools like introductory graphs, such as Figure 2, which may be considered as archetypal. Hence, it is worth studying the decisions made by textbook authors when choosing the features of their archetypal graph and any additional graphs included in the chapter or section on compaction. Study of the graphs confirmed a common trend in introductory geotechnical engineering textbooks when comparing older textbooks (from the previous century) with more recent textbooks. In recent textbooks, many x-y graphs are conceptual sketches using axes without numbers. What is more, for the chapters/sections on compaction surveyed herein, most graphs are for unnamed soils! It can be argued that such sketches are closer to cartoons than to engineering graphs. Teaching with cartoons has two undesirable side effects. First, students are not given opportunities to pay attention to values and develop a sense of what numbers to expect for the parameters on the x-y axes. (The excuse “I do not want to confuse my students with details” is not valid, because we can make hybrids, i.e. axes with orders of magnitude; perhaps these are the best for introductory textbooks.) The second effect is even more unfortunate: the rich variety of soils disappears when a single curve is presented, which –when no specific soil is mentioned– becomes representative of all soils. This is a problem for compaction, as we will see in the next section; the problem with “one graph fits all soils” is partly addressed in Section 7.1.3.

6.2.3 Textbooks: unanswered questions

Difficulties encountered by topics to be taught do not concern only students. Many instructors, including the author, have areas in which their knowledge is not especially strong. If their instructional decisions make them avoid these topics, they miss opportunities to spot potential knowledge gaps not only of their own but of other colleagues as well and even of the entire geotechnical engineering community. As already mentioned, soil compaction is an empirical topic that might be perceived as non-challenging for students (an assumption not necessarily valid as discussed in Sections 5 and 6.2.1). The conscientious instructors who have to teach compaction and will learn to teach compaction from textbooks will come against at least two unanswered questions, as discussed next.

Compaction basics in textbooks applicable to all soils?

To prepare this paper, the author approached the topic of soil compaction through the perspective of her specialization in environmental geotechnics; soil compaction is prerequisite background for the

compacted clay used in landfill liners. The compaction basics presented in Section 5 make intuitive sense for clays, since we all have first-hand experience with surficial clayey soils and how hard they can become when dry or nearly dry; it makes sense that we need to add water. But what about coarse-grained soils without any significant fine-grained content? Whereas in practice both coarse-grained and fine-grained soils are compacted, the *theory* of compaction –as described in Section 5– appears to be appropriate for fine grained soils. The fact that recent textbooks provide no help with this question was the prompt to include in the textbook survey classic textbooks in soil mechanics either published or with first editions in the 1940s (Taylor, 1948; Terzaghi & Peck, 1967). In these books, the sections on compaction start from the early work of R.R. Proctor on compacted soils for earth dams, i.e. an application for which –similar to landfill liners– a significant fine-grained soil fraction is necessary. Terzaghi & Peck (1967) implicitly stress differences by devoting separate sections to clean coarse-grained sands and gravels. Lambe and Whitman (1979) refer vaguely to differences in the following sentence: “Cohesionless soils do not respond to variations in moisture content and compactive effort in the manner characteristic of fine-grained soils”. However, because this sentence accompanies a specific figure (Fig. 34.5), the difference may be interpreted to refer only to capillary effects (for details see Text S1 in Online Supplement). Only Bowles (1984) writes unequivocally that for cohesionless soils “a curve is usually not drawn to obtain maximum density”. The more recent textbooks offer no hint that archetypal compaction curves, such as Figure 2, may not be relevant to coarse-grained soils. As a side note, older textbooks categorize soils as cohesive or cohesionless, a practice now often discouraged (e.g. Burland, 2012) but by necessity followed herein to remain faithful to the original distinctions made in the surveyed textbooks.

What saturation values to expect at and past the optimum point?

The second unanswered question concerns the degree of saturation, S , a parameter one could decide is of secondary importance judging by its cursory treatment in most textbooks. From the reviewed textbooks, Terzaghi & Peck (1967) make no reference to the degree of saturation in their section on soil compaction. In many of the other textbooks, the degree of saturation appears indirectly when the archetypal compaction curve includes, in addition to the zero air voids line at $S=100\%$, at least a second constant S curve, like in Figure 2. Through the years, the author had seen several such graphs, and her recollection was that the optimum points and the descending branches of compaction curves were at some “saturation distance” from the zero air voids line, around 10%-15%. Such recollection is consistent with the difficulty of removing air once occluded, e.g. Powrie (2014) mentions that it will be virtually impossible to remove by compaction any remaining air pockets at $S=90\%$. The first surprise was the set of indicative compaction curves presented by Knappett and Craig (2012) in their Figures 1.17 and 1.18 to demonstrate the effects of different compactive efforts and of different soils. The optimum points are at, or close to, a degree of saturation $S = 95\%$, while the descending branches of a few curves reach very close to the zero air voids line. Being indicative, these graphs could be dismissed as unsupported by evidence. However, Knappett and Craig (2012) also provide a second set of figures for four specific soils of known particle size distribution (Fig. 1.19a) contrasting laboratory compaction and different methods of field compaction (Figs. 1.19b-e). These valuable figures were redrawn and are included in the Online Supplement (Figures S3 – S7). Comparing the two sets of curves in Knappett and Craig (2012) suggests that the indicative curves might have been inspired by the experimental curves. Knappett and Craig (2012) is not the only textbook with compaction curves close to zero air voids line. The archetypal compaction curves in Terzaghi & Peck (1967) are very close to the zero air voids line; one of them is almost touching. But perhaps it is not meant as archetypal, because it is discussed in the section on sands-silts with moderate cohesion. Maybe a useful clue is given by Lambe & Whitman (1979), who have an archetypal curve not exceeding $S \approx 90\%$ (Fig. 34.1), and another “typical compaction curve for cohesionless sands and sandy gravels” (Fig. 34.5) with two optimum points of equal density, one when the sand is completely dry and the other at complete saturation. The author’s tentative conclusion is that the second unanswered question is part of the first one. How far away from saturation are the optimum points may depend on whether we have more or less fines. Another factor that may inadvertently complicate the issue is the choice of specific density, G_s , if it is not measured but assumed (for a larger value of G_s , the line of 100% degree of saturation moves to the right, i.e. away from the compaction curve). For this reason, compaction graphs with constant degree of saturation lines should indicate the value of G_s used in their calculation.

7 Soil compaction: Targeted teaching material

7.1 Adding to the pedagogical knowledge of soil compaction

The textbook survey (Sections 6.2.2 and 6.2.3) informed the creation of new figures designed to support specific pedagogical decisions. Some figures are included in this paper. All figures are included in the Online Supplement, which is made available under a Creative Commons (CC) license “attribution only” (i.e. CC BY), following the recommendation by Fellin (2025). The list of contents of the supplement is included in Table A1 in the Appendix. The description of each figure starts with its target, i.e. the pedagogical goal it was created to achieve. Stating a target is key. First, the target guides instructors to use teaching material if they find it worthwhile. Second, if the target is worthwhile but the execution falls short, someone else can improve upon it.

7.1.1 Target: help students explore alternative ways to describe how dense soil is

Figure 3 is an incremental improvement on Taylor's (1948) idea of using a triple vertical axis for the compaction plot. Instead, Figure 3 shows data from the same compaction test in three different plots of dry unit weight, γ_d , porosity, n , and void ratio, e , as a function of water content, w . We saw in Section 4.1 that the pedagogical knowledge of content includes difficulties of students and in Section 6.2.1 that alternative measures to represent soil density are not equivalent from a cognitive point of view. When compaction is taught early in an introductory course, students have just been bombarded with a significant number of new parameters. [The new parameters are introduced in a section typically and opaquely called “Phase relationships”; Frenlund and Rahardjo (1993) use the better alternative “Volume-mass relationships”.] The shape of the three graphs in Figure 3 conveys the message that each of the three parameters measures the same fundamental aspect of the soil, in two reciprocal ways: dry unit weight measures the space occupied by soil particles, while porosity and void ratio measure the space left between soil particles. The γ_d axis increases upwards, conveying the message we want high values, while the n and e axes increase downwards, conveying the message we want small values. Considering the three graphs from a visual literacy point of view, it may be easier for the students if the water content axis is placed at the top of graphs (b) and (c), to stress further that porosity and void ratio increase downwards. For this reason, both versions are included in the Online Supplement (Figures S9-S10). Figure 3 restores the importance of porosity, n , an unsung parameter in soil mechanics, but *the* key parameter to describe pore space in other civil engineering disciplines (Section 6.2.1). Finally, Figure 3 lends itself also to a discussion on the ranges of these parameters, with prompts such as: “For this test, we need to plot only the range for the measured values of the three parameters. What would be a range suitable for all soils, not only compacted? Are there any bounding values?”. While instructors may think that these questions rephrase the obvious, some students may be grateful for the opportunity to ponder some more on the soils' parameters in the context of an application, in addition to the usual assignments of calculating numbers.

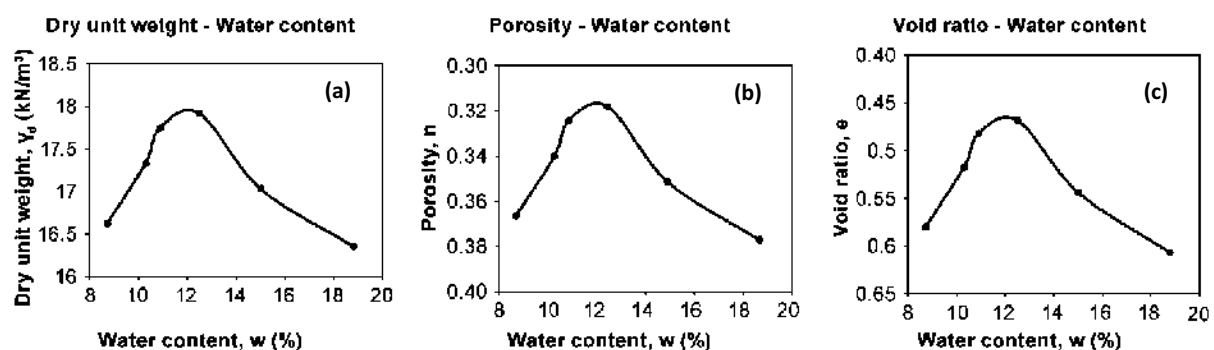


Figure 3. Results from the same compaction test are plotted with water content, w , on the x axis and three different measures of density on the y axis: (a) dry unit weight, γ_d , (b) porosity, n , and (c) void ratio, e . The similar shape of the curves indicates that the three measures are equivalent in conveying the effect of compaction. Data obtained from Das (1997).

7.1.2 Target: promote degree of saturation as a key soil parameter (despite its unsuitability to replace water content for compaction specifications)

Like porosity, the degree of saturation is another very useful quantity in areas beyond the historical core of geotechnical engineering, such as environmental geotechnics and unsaturated soil mechanics. One of the author's motivations for delving deeper into soil compaction was the opportunity to explore plotting compaction data as a function of the degree of saturation. But, alas, the dry unit weight – degree of saturation curve in Figure 4b has such an awkward shape! Two more data sets plotted were comparably disappointing. The author would be prepared for the disappointment, had she remembered better what she had underlined as a graduate student in Lambe & Whitman (1979):

“As can be seen in Figure 34.1, the degree of saturation increases with increasing water content to a value somewhat above that at optimum moisture content and then tends to remain approximately constant.”

However, the contrast between the graphs with water content (Figure 4a) and degree of saturation (Figure 4b) serves another useful purpose, in addition to calling attention to the degree of saturation in a backhanded manner (akin to the well-known paradox of being told “don't think of an elephant”), which is to explain compaction specifications. As already mentioned, we specify a desirable high percentage of the maximum unit weight, γ_{dmax} , which is equal to 95% in Figure 4. In the field, this specification is translated as follows: if we work with water contents around the optimum water content of 12% on either side, i.e. between 10% and about 14% for the soil depicted in Figure 4, we are likely to be close to γ_{dmax} . The same would not be true if we defined an optimum degree of saturation, because soon after it is exceeded the unit weight becomes unacceptably low. This rapid decrease of density to the right of S_{opt} is especially problematic for applications where it is desirable to compact at higher rather than lower water contents to obtain the same γ_d , e.g. see Lambe & Whitman (1979). However, as Bicalho (2025) points out, Tatsuoka and Correia (2016) argue for specifying not only dry density and water content, but also S_{opt} , which –for the same compaction method– is not sensitive to the energy level, e.g. see Text S1, note on Lambe & Whitman (1979) in Online Supplement.

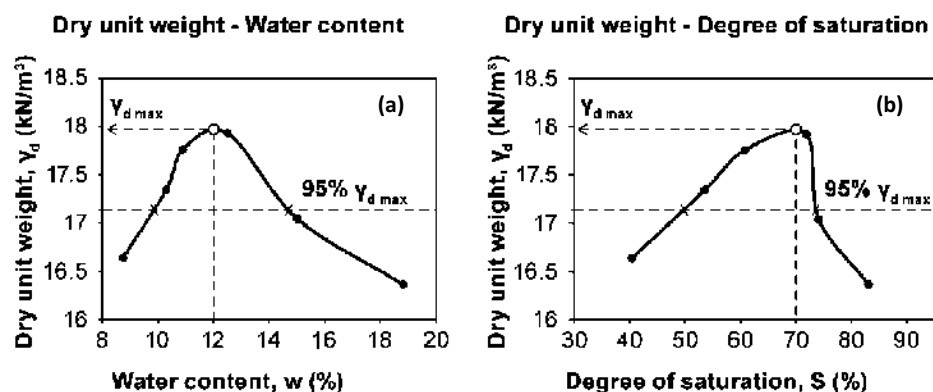


Figure 4. Results from the same compaction test are plotted as dry unit weight, γ_d , against (a) water content, w , and (b) degree of saturation, S . Data obtained from Das (1997), values of degree of saturation computed for $G_s=2.68$.

7.1.3 Target: stress the variety of compaction curves (even for a subset of soils with sizeable fine-grained fraction)

To dispel the notion that a couple archetypal compaction curves (like the two depicted in Figure 2) fit all soils, it is recommended to include in instruction compaction curves for a variety of specific soils, ideally classified according to the Unified Soil Classification System (USCS) and accompanied by their particle size distribution curve. As already mentioned, such a set (except for the USCS classification) is found in only one of the surveyed textbooks (Knappett & Craig, 2012). To make the set available to interested instructors, the figures were redrawn from their original source (Croney & Croney, 1998) and included in the Online Supplement (see Figures S3-S7). As already mentioned, the set compares results from laboratory compaction and from 3-4 field compaction methods. Perusal of all the curves obtained for each soil with different compaction methods and energies in the field shows that optimum points do not fall on a line of constant degree of saturation. However, for compaction curves obtained with the same

compaction method but different compactive energy, specifically the British Standards (BS) standard compaction (light or normal compaction) and heavy compaction (termed modified compaction in other standards), the line defined by the optimum points goes in the same general direction as the lines of constant degree of saturation. It is possible that the different compaction methods create a different soil fabric, which is reflected in the different degrees of saturation at the optimum points (see also Section 7.2).

7.1.4 Target: guide students to think about the role of soil particles in defining the soil's personality (big idea)

From the surveyed textbooks, only Bowles (1984) and Knappett & Craig (2012) have graphs showing compaction curves for a variety of soils on the same plot. The graph by Bowles (1984) (Fig. 7-2) shows clearly that the highest value of maximum dry unit weight, γ_{dmax} , is achieved for the coarsest soil on the graph, a well-graded loamy sand, and then gradually decreases for silty soils and even more for clayey soils. The decrease is impressive: as the fine-grained percentage (passing the No 200 sieve) increases from a well-graded sand to a heavy clay, γ_{dmax} decreases monotonically from $\sim 21 \text{ kN/m}^3$ to $\sim 15 \text{ kN/m}^3$. A poorly graded sand also gives a low density with the standard compaction method.

No graph was found to display the combined effect of soil type and compactive energy. To this end, the pair of the light (or normal) and heavy compaction curves obtained in the laboratory was selected from each of the four graphs from Croney & Croney (1998) and plotted on a single graph, shown in Figure 5. The decision to omit from Figure 5 the name of the standards followed to obtain the compaction data was consistent with archetypal Figure 2. The decision brought about the need to use the descriptive terms “light” and “heavy” compaction. (Figure S8 in the Online Supplement includes a variation of Figure 5 with descriptive terms “normal” and “heavy” compaction and is accompanied by a preliminary discussion in Text S2 on the relationship between the various standard procedures, which was not found in any of the surveyed textbooks.) Again, we see in γ_{dmax} a general decreasing trend for increasing percentage of fines (from $\sim 21.6 \text{ kN/m}^3$ to $\sim 15 \text{ kN/m}^3$). But, now that the compactive energy and the soil type are combined, the decrease is not monotonic anymore. Coarse-grained soils are clustered together at higher maximum dry densities from $\sim 2050 \text{ kg/m}^3$ to 2200 kg/m^3 ($\sim 20.1 \text{ kN/m}^3$ to $\sim 21.6 \text{ kN/m}^3$), but the sand undergoing heavy compaction is denser than the gravel-sand-clay soil undergoing light (or normal) compaction. Similarly, a plastic clay undergoing heavy compaction is denser than a sandy clay undergoing light (or normal) compaction.

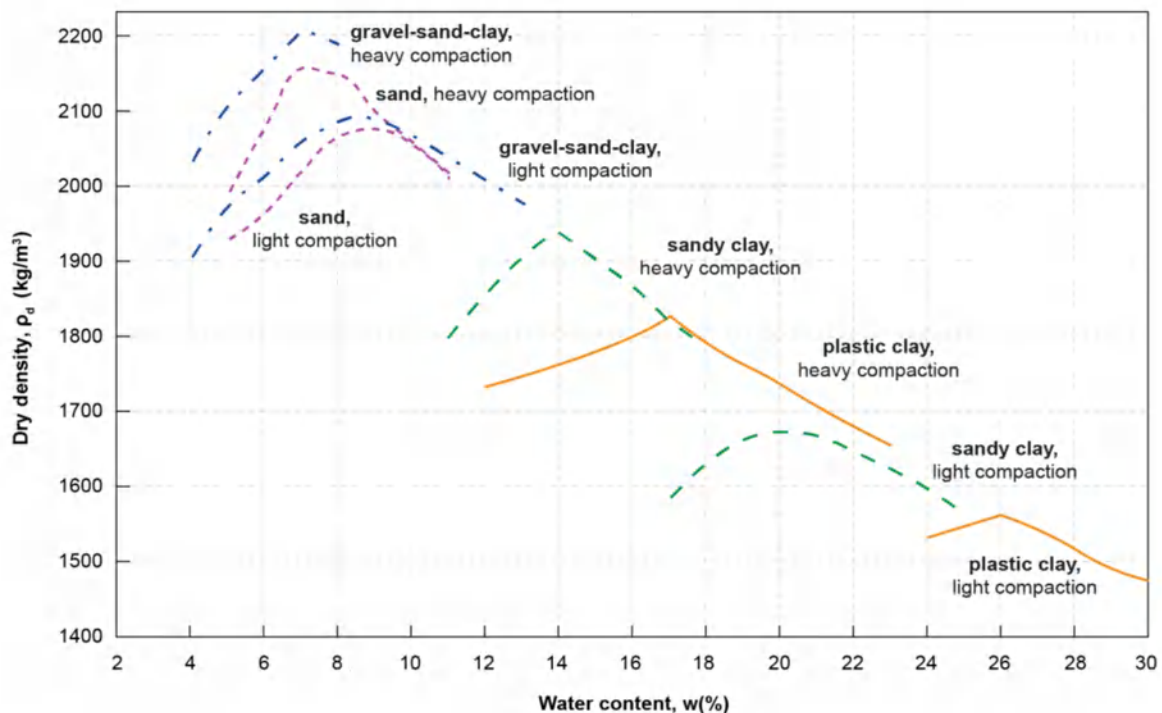


Figure 5. Compaction curves of four different soils obtained using two compactive efforts demonstrate the effect of soil particles across soil types: soil particles are to soil what yarn is to textile. Data obtained from Croney & Croney (1998).

By combining the effect of the energy (stressed in all textbooks) and the effect of the soil type (highlighted in few textbooks), Figure 5 manages to demonstrate the effect of soil particles across soil types, an idea that transcends the topic of compaction. The role of soil particles as the fundamental units of soils that determine the material's fabric and behavior is well established and stressed often in soil mechanics. But the variety of the soils that can result from the same soil particles is not discussed. Herein it is suggested we describe both ideas with one analogy: *soil particles are to soil what yarn is to textile*. We can make a variety of textiles with the same yarn, but we cannot make any textile we want with a specific yarn. The yarn will always impose some constraints on the final textile produced. By compacting the same soil in the laboratory with different levels of compaction energy, we can demonstrate the variety of the resulting soil material from the same soil particles. By showing in the same graph different soils and different compaction energies, we can demonstrate the limitations imposed by the soil particles on the resulting soil material. From this perspective, the instructor can use compaction as a vehicle to a big idea to be reinforced later in the geotechnical curriculum, e.g. when discussing the quantitative differences between clays and sands.

7.2 Potential future goals

This section lists provisional thoughts about how soil compaction could enrich the way we teach soil mechanics.

- The sensory perception of pressing with a finger on compacted soil is a revelation, because it feels harder than anything we normally associate with soil! Perhaps compaction can free us from thinking of soil as the material on the earth's surface that runs through our fingers when we hold it in our hands. Compaction can also help us imagine how competent an overconsolidated soil can be, considering that compaction increases the lateral effective stress, similarly to the application and removal of static load to a confined soil sample (Lambe & Whitman, 1979). As a side benefit, such a pedagogical decision will help dispel impressions that we pull values out of a hat for the coefficient of lateral earth pressures at rest, K_0 .
- Compaction for the non-specialist was presented herein as "building with soil", which is contrasted with the more common "building on soil". Given the variability of the natural material we build on, maybe it would be helpful to start instruction from the material we build with, i.e. compacted soil, over which we have some control. To the author's knowledge, the unsaturated soils community has not pursued such an approach, with the possible exception of Vulpe & Beckett (2025), who introduce in an elective geoenvironmental course basic concepts from unsaturated soil mechanics using as an example rammed earth (a traditional construction method using highly compacted unsaturated soil blocks). On the contrary, a highly cited textbook on unsaturated soils includes the following statement, which implies that unsaturated soil mechanics cannot bring any new knowledge to compaction: "The compaction process is not discussed in this book, since numerous soil mechanics textbooks deal with this subject." (Frendlund & Rahardjo, 1993, p. 33). This apparent disowning of soil compaction by at least part of the unsaturated soils community appears to be a missed opportunity, as argued also by Bicalho (2025).

8 Combining changes in scale, attitude and organization of logistics

Section 3.1 established that geotechnical engineering instructors do not have all the educational materials they would wish for. Studying from a teaching point of view each topic in the manner presented in Section 6 for soil compaction would augment the list of needs. Instead of being overwhelmed though, we can be hopeful because the pilot for soil compaction presented in Section 7 shows that work can be done piecemeal by reducing the scale of the contribution. Small scale was interpreted herein in two senses. The scope was limited to studying how one topic only is treated in different textbooks, and the ambition was limited to adding something small. The author experienced the comparative analysis of textbooks as a privilege allowing her to serve as a go-between, bringing the ideas of Taylor, Terzaghi, Peck and many more into dialogue. It would be a benefit to education if this service were valued more highly. This is the last attitude change advocated herein. It changes the perception of a go-between from someone who almost runs on errands, to someone who –for specific topics– can unlock everyone's mind, including some of the finest. It might be the most difficult change, as it calls for valuing a

scholarship appreciated in the humanities, and even there perhaps in the more esoteric disciplines. For example, we can easily imagine in philosophy the prestige of a go-between for Plato and Aristotle.

Small scale makes manageable also the task of peer review discussed in Section 3.2. To ensure adequate output of educational materials with small-scale contributions we need many developers. Hence, we need to combine reductions in scale with crowdsourcing. An example of reduced scale and crowdsourcing is the Geotechnical Engineering Education Post (GEE Post) “Short geo-engineering video quizzes on-demand” by Calvello (2022). The post is a personal reflection by Calvello on a collection of 3-5 min videos, called “geo-engineering pop-quizzes” by their developer Timothy Stark. The post is accompanied by reviews by several TC306 members of video quizzes that attracted their attention. Another example is the mobilization of a teacher’s network to provide input for the development of the geotechnical engineering concept inventory by Kirsch et al. (2025), mentioned in Section 4.2. Given that the need for assessment materials was clearly mentioned by the respondents to the survey on educational material by Pantazidou and Calvello (2024), perhaps the choice of a concept inventory as a research topic by Kirsch et al. (2025) is related to their having access to ideas and thoughts by a large number of colleagues. Identifying needs for teaching materials, managing crowdsourcing and facilitating systematic practice of peer review; all require some coordinating infrastructure, which can be offered by a technical committee assuming the new role of a knowledge broker. This future entails that technical committees on education assume an active role and even commission teaching materials based on their specifications.

9 Summary and conclusions

- Advocated change in attitude concerning educational materials

Data from a questionnaire have showed that a large percentage of geotechnical engineering instructors are not satisfied with their educational materials. Acknowledging a need is the first step to address it.

- Advocated change in attitude concerning peer review of educational materials

Evidence from the education literature indicates that students’ perceptions on what helps them learn are not accurate. This intensifies the need for peer review of educational materials.

- Advocated change in the organization of content when developing educational materials using the framework of pedagogical content knowledge

The framework of pedagogical content knowledge provides guidance for the development of teaching and learning materials, with its emphasis on explanations and its explicit acknowledgement of different perceptions of content. Some of the perceptions of instructors may provide extra guidance to students. Big ideas and key concepts within the disciplines complete the framework by guiding developers to the topics being worth gathering their respective pedagogical knowledge.

- Advocated change in attitude concerning the developer of educational materials

Within the framework of pedagogical content knowledge, teachers record tacit experience-based knowledge –dispersed in textbooks and their own– and create new knowledge in their role of a go-between for people and ideas. It will help if the role of the go-between is upgraded from that of an errand-runner to that of a thought discoverer.

- Developing educational materials for a specific topic using the framework of pedagogical content knowledge reinforces the framework itself

To the pedagogical knowledge of soil compaction extracted from textbooks, the author added her own through the development of teaching materials, which were described as an example application. The framework provided guidance for the development of materials for soil compaction and the development of materials enriched the framework. Perhaps all examples have an enriching effect. In particular, examples that introduce previously unacknowledged types of knowledge may enrich our understanding in especially significant ways.

- How can the advocated changes be facilitated and by whom?

The dual burden of producing and reviewing new teaching materials becomes manageable by (i) focusing on big ideas and key concepts, (ii) reducing the scale of the contributions and (iii) crowdsourcing. Entities such as technical committees on education and teacher’s networks can serve

as knowledge brokers and perhaps Centers for Teaching and Learning, as well as Departments of Engineering Education can offer support.

Acknowledgements

The author thanks Christos Stratakis, Vasilis Boukouvalas and Ilias Kevrekidis for the in-house soil compaction tutorial at NAMALAB, the GEE 2025 authors whose papers she had the privilege of reading before the conference, Nicolas Op de Beeck for providing peer review (as a peer professional) of the part of Section 5 meant for a general professional audience, Michele Calvello from providing –once more– thoughtful comments on both details and structure, Alexandra Theodoraki and Christos Kentrotis for preparing the graphs for the paper and the supplement, and acknowledges ChatGPT for assistance with language and idea refinement.

References

- Ambrose, S.A., Bridges, M.W., DiPietro, M., Lovett, M.C., Norman, M.K. (2010). *How learning works: 7 researched-based principles for smart teaching*. Jossey-Bass, San Francisco, USA.
- Atkinson, J. (2016). First John Burland Lecture: Basic Geotechnical Engineering Skills - What Can Graduates Do? ISSMGE Int. Conf. Shaping the Future of Geotechnical Education SFGE 2016, Belo Horizonte, Brazil, Oct. 19-20, <https://www.issmge.org/education/videotaped-honor-lectures/first-john-burland-lecture>, (accessed May 28, 2025).
- Ball, D.L., Cohen, D.K. (1996). Reform by the book: What is –or might be– the role of curriculum materials in teacher learning and instructional reform? *Educational Researcher*, 25(9), pp. 6-8,14.
- Bicalho, K.V. (2025). Why unsaturated soil mechanics is relevant to civil engineers. *Proc. of the ISSMGE Int. Conf. Geotechnical Engineering Education 2025 (GEE 2025)*, Calvello, M., Pantazidou, M., Pinho-Lopes, M. (Eds.), Nancy, France, July 2-4.
- Bohnhoff, G., Sample-Lord, K., Hubler, J., Strandberg, N., Walleiser, J. (2025). Development of shareable activity library for geoenvironmental engineering education. *Proc. of the ISSMGE Int. Conf. Geotechnical Engineering Education 2025 (GEE 2025)*, Calvello, M., Pantazidou, M., Pinho-Lopes, M. (Eds.), Nancy, France, July 2-4.
- Bolton, M. (1979). *A Guide to Soil Mechanics*. Macmillan Press, London and Basingstoke, UK.
- Bowles, G.E. (1984). *Physical and Geotechnical Properties of Soils*, 2nd edition (1st edition 1979). McGraw-Hill, New York, USA.
- Burland, J.B. (2012). Soils as particulate materials, in: Burland, J., Chapman, T., Skinner, H. and Brown, M., Eds. (2012). *Institution of Civil Engineers (ICE), Manual of Geotechnical Engineering*, Vol. I, Chapter 14, ICE publishing, London, UK.
- Calvello, M. (2022). Short geo-engineering video quizzes on-demand. *Geotechnical Engineering Education Post* https://www.issmge.org/filemanager/technical_committee_pages/54/GEEpost_2022-06-30_Calvello.pdf
- Calvello, M. (2025). Teaching soil mechanics core concepts: mapping the structure of university textbooks worldwide. *Proc. of the ISSMGE Int. Conf. Geotechnical Engineering Education 2025 (GEE 2025)*, Calvello, M., Pantazidou, M., Pinho-Lopes, M. (Eds.), Nancy, France, July 2-4.
- Croney, D., Croney, P. (1998). *The design and performance of road pavements*, 3rd ed. (1st ed. 1977). McGraw-Hill, New York, USA.
- Das, B.M. (1997). *Soil mechanics laboratory manual*, 5th ed. (1st ed. 1982). Engineering Press, Austin, Texas, USA.
- Davis, E., Janssen, F., Van Driel, J. (2016). Teachers and science curriculum materials: where we are and where we need to go. *Studies in Science Education*, 52(2), pp. 127-160.
- Deslauriers, L., McCarty, L.S., Millerc, K., Callaghana, K., Kestina, G. (2019). Measuring actual learning versus feeling of learning in response to being actively engaged in the classroom. *Proceedings of the National Academy of Sciences (PNAS)*, 116(39), pp. 19251–19257.

- Fellin, W. (2025). Open Educational Resources for geotechnical engineering education. Proc. of the ISSMGE Int. Conf. Geotechnical Engineering Education 2025 (GEE 2025), Calvello, M., Pantazidou, M., Pinho-Lopes, M. (Eds.), Nancy, France, July 2-4.
- Frendlund, D.G., Rahardjo, H. (1993). Soil Mechanics for unsaturated soils. Wiley, New York, USA.
- Jaksa, M.B. (2020). Reflections on some contemporary aspects of Geotechnical Engineering Education – From critical state to virtual immersion, 2nd John Burland Lecture. Proc. of the ISSMGE Int. Conf. Geotechnical Engineering Education (GEE 2020), Pantazidou, M., Calvello, M., Pinho-Lopes, M. (Eds.), streamed from Athens, Greece, June 23-25. <https://www.issmge.org/uploads/publications/3/102/Jaksa.pdf> (accessed May 28, 2025).
- Kirsch, A., Fellin, W., Sonnenberg, R. (2025). Developing concept inventories for Geotechnical Engineering. Proc. of the ISSMGE Int. Conf. Geotechnical Engineering Education 2025 (GEE 2025), Calvello, M., Pantazidou, M., Pinho-Lopes, M. (Eds.), Nancy, France, July 2-4.
- Knappett, J.A., Craig, R.F. (2012). Craig's Soil Mechanics, 8th edition (1st edition 1974). Spon Press, London, UK.
- Kruger, J., Dunning, D. (1999). Unskilled and unaware of it: How difficulties in recognizing one's own incompetence lead to inflated self-assessments. J. of Personality and Social Psychology, 77(6), pp. 1121-1134.
- Lambe, T.W., Whitman, R.V. (1979). Soil Mechanics, SI Version (1st edition 1969). Wiley, New York, USA.
- Moore, T. (2024). Personal communication, August 26, 2024.
- Pantazidou, M., Calvello, M. (2024). What kinds of educational material are useful for and desired by university instructors? The case of Geotechnical Engineering. Soils and Rocks, 47(2), e2024003623, <https://doi.org/10.28927/SR.2024.003623>
- Powrie, W. (2014). Soil Mechanics Concepts and Applications, 3rd ed. (1st ed. 1996). CRC Press, Taylor & Francis Group, Boca Raton, USA.
- Shulman, L.S. (1986). Those who understand: Knowledge growth in teaching. Educational Researcher, 15(2), pp. 4-14.
- Skoumios, M., Skoumpourdi, Ch. (2018). Use of educational material for Mathematics and Physics. Proc. 3rd Hellenic Conference on Educational Material for Mathematics and Physics, Rhodes Island, Greece, Nov. 9-11, pp. 18-65 (in Greek).
- Tatsuoka, F., Correia, A.G. (2016). Importance of controlling the degree of saturation in soil compaction. Procedia Engineering, 143, pp. 556-565.
- Taylor, D.W. (1948). Fundamentals of Soil Mechanics. John Wiley, New York, USA.
- Terzaghi, K., Peck, R.B. (1967). Soil Mechanics in Engineering Practice, 2nd ed. (1st ed. 1948). John Wiley, New York, USA.
- Vulpe, C., Beckett, C.T.S. (2025). Teaching unsaturated soil mechanics through rammed earth. Proc. of the ISSMGE Int. Conf. Geotechnical Engineering Education 2025 (GEE 2025), Calvello, M., Pantazidou, M., Pinho-Lopes, M. (Eds.), Nancy, France, July 2-4.
- Wiggins, G., McTighe, J. (2005). Understanding by design, Expanded 2nd edition. Association for Supervision and Curriculum Development, Alexandria, USA.
- Yadav, A., Shaver, G.M., Meckl, P. (2010). Lessons learned: Implementing the case teaching method in a mechanical engineering course. J. of Engineering Education, 99(1), pp. 55-69.
- Yadav, A., Alexander, V., Mehta, S. (2019). Case-based Instruction in Undergraduate Engineering: Does Student Confidence Predict Learning? Int. J. of Engineering Education, 35(1A), pp. 25-34.

Appendix

Table A1. List of contents of Online Supplement^a

Contents	Page
Table S1. Introductory and specialty textbooks surveyed for the topic of soil compaction listed in order from oldest to most recent based on their first edition dates	2
Text S1. Annotated list of references of the surveyed books	3
Figure S1. Proposed textbook-case graph of compaction curves obtained in the laboratory (Figure 2 in paper) with commentary on key features	8
Figure S2. Compaction curves plotted as specific volume, v , against water content, w : graph by Powrie (2014), included with permission by the author	10
Figures S3-S7. Set of one figure with grain size distribution curves of four soils and four figures, one for each soil, with compaction curves obtained in the laboratory at different levels of compactive energy and in the field using different compaction methods	11
Figure S8. The big idea “soil particles are to soil what yarn is to textile” is illustrated with compaction curves of four different soils (Figure 5 in paper)	14
Figures S9-10. Examples of compaction curves using different measures of density (Figure 3 in paper)	15
Figure S11. Compaction curves with dry unit weight plotted against water content or degree of saturation (Figure 4 in paper)	17
Text S2. Note on compaction standards (tentative)	18
Text S3. Note on static vs dynamic compaction (conjectural)	21

^a Link: <https://www.mygeoworld.com/file/139984/supplement-to-the-3rd-burland-lecture-by-m-pantazidou>

Author's bio

Marina Pantazidou, National Technical University of Athens, Greece

Marina Pantazidou is an associate professor at the Civil Engineering School of the National Technical University of Athens, Greece. Apart from university appointments in the US and Greece, her professional experience also includes work in hazardous waste consulting. Her research topics are drawn from environmental geotechnics and engineering education. She is author of 100 publications, 25 of which on geotechnical engineering education topics. She has been a guest editor for two special issues on geotechnical engineering education, one on case studies developed for geotechnical engineering instruction. She has been actively involved with the Hellenic Society for Soil Mechanics and Geotechnical Engineering (secretary general 2012-2015 and board member 2015 -) and the ISSMGE Technical Committee TC306 on Geo-engineering Education (core member 2010-2013, vice chair 2013-2017, chair 2017 -). She chaired the ISSMGE Int. Conf. on Geotechnical Engineering Education GEE2020, (streamed from) Athens, Greece, June 23-25, 2020.

Invited Papers

Teaching of unsaturated soil mechanics: building on fundamental physical mechanisms to pave the way for geotechnical analyses

A. Amabile & A. Tarantino

University of Strathclyde, Glasgow, Scotland (UK)

alessia.amabile@strath.ac.uk, alessandro.tarantino@strath.ac.uk

ABSTRACT: Unsaturated soil mechanics is typically not included in traditional geotechnical engineering curricula at undergraduate level and the design and development of specific modules is usually left to the initiative of individual academics, very often already involved in unsaturated soil mechanics' research. Due to the lack of advanced testing equipment for unsaturated soils, even when principles of unsaturated soil mechanics are added to the curriculum, they typically lack the laboratory component usually included in traditional geotechnical engineering courses. This paper presents an innovative approach to teach unsaturated soil mechanics starting from elementary physical mechanisms. One of the distinctive features of this approach is using real-time, small-scale experiments to provide a visual demonstration of key micromechanisms of unsaturated soil mechanics, such as surface tension and capillary forces. This offers the opportunity to enhance students' engagement and at the same time help them develop a deeper understanding of the fundamentals of unsaturated soil mechanics by presenting them in a non-axiomatic fashion. The proposed approach also focuses on providing numerical tools that enable students to carry out simple, introductory analyses of unsaturated geostructures. In this approach, content is introduced by building upon concepts and methodologies that are typically familiar to undergraduate students, making it accessible and easy to implement across different universities.

Keywords: *Unsaturated soils, Undergraduate teaching, Capillary tubes, Capillary forces, Slope stability analysis*

1 Introduction

Teaching of unsaturated soil mechanics is not part of routine soil mechanics courses at undergraduate level. The topic is hardly covered by any introductory soil mechanics textbook and its inclusion in the undergraduate teaching curricula is mostly driven and developed by academics whose area of expertise is unsaturated soil mechanics. Even within this community there are disagreements about which key concepts should be included in a course and about how to deliver the content to students in the most effective way (Pantazidou *et al.*, 2024). This makes it extremely challenging for academics whose research interests lie elsewhere to integrate principles of unsaturated soil mechanics in their teaching, thus limiting access and preventing a more widespread inclusion of these topics in undergraduate programmes.

In most soil mechanics courses students' learning can often be enhanced by laboratory activities carried out with traditional geotechnical engineering testing equipment (e.g. soil classification, triaxial and shear tests, permeability tests). However, carrying out experimental activities on unsaturated soils requires specialised equipment, which is typically unavailable in most university research laboratories, and even more so in teaching laboratories.

This paper presents an innovative approach for the design and development of an unsaturated soil mechanics course at undergraduate level. The approach focuses on two main aims; firstly, to help students develop an understanding of the fundamentals of unsaturated soil mechanics starting from elementary physical mechanisms, with the support of physical models, and then to provide them with quantitative tools to carry out simple, introductory analyses.

Overturning the most common approach, in which mathematical models are fitted on experimental data, in this approach mathematical models are derived from elementary physics mechanisms which are also

visually demonstrated by practical experiments. Everyday objects are used to carry out real-time, small-scale experiments in a classroom setting, aimed to present key micromechanisms such as capillarity and water retention. This offers a powerful tool to enhance students' engagement and help them navigate the complexity of unsaturated soil mechanics. This approach, therefore, also overcomes the challenges associated with introducing a practical component to the teaching of unsaturated soil mechanics.

Within the context of geotechnical engineering, new content is introduced by building upon concepts and terminology that are already familiar to undergraduate students, such as pore water pressure, effective stress and shear strength, in order to make this more accessible to students (and academics who have different areas of expertise). This principle is also followed with regard to the quantitative tools, where unsaturated soil mechanics models are introduced in the framework of methods that are routinely employed in traditional 'saturated' geotechnical engineering analyses. It is essential to highlight that the aim of these quantitative tools is simply to allow students to explore and appreciate the effect of unsaturated soil behaviour on the order of magnitude of the outcome of stability analyses. This preliminary analysis is considered as a first step for students to develop critical thinking skills and make their own judgement about whether further, more advanced analyses would be necessary or beneficial on a case-by-case-basis.

For the scope of this paper, the practical applications refer to slope stability problems in which suction profiles have been assumed hydrostatic and a simplified shear strength criterion has been adopted in the calculations. However, the approach could easily be extended to different geotechnical engineering problems and account for different suction distribution profiles and more complex variables such as rainfall.

2 Historical barriers to undergraduate teaching of unsaturated soil mechanics

Lecturers not involved in unsaturated soil mechanics research find it difficult to approach this subject due to the 'unsaturated' jargon often encountered in books and research papers. This section breaks down some of these barriers to smoothen the transition from saturated to unsaturated soil mechanics.

2.1 Suction versus pore-water pressure

Undergraduate textbooks dealing with the mechanics of saturated soils introduce the concept of pore-water pressure (u_w), i.e., the pressure of the water residing in the pore-space. Pore-water pressure drives water seepage (via the hydraulic head) and controls soil mechanical behaviour (via the 'saturated' Terzaghi's effective stress). It can be measured using a piezometer in contact with the soil through a porous filter (to allow water to transfer from the soil to the instrument or vice versa). The concept of pore-water pressure is simple to understand and is defined operationally by a simple measurement technique, based on the Stevin's principle of communicating vessels.

Fredlund and Rahardjo (1993) published the first book on unsaturated soil mechanics, a book that is still a reference for undergraduate students and lecturers approaching unsaturated soil mechanics for the first time. They introduce an apparently new concept, the 'suction'. Similarly to the pore-water pressure in saturated soils, soil suction in unsaturated soils drives water seepage and controls mechanical behaviour.

Following Fredlund and Rahardjo (1993), soil suction ψ is defined as the free energy state of soil water. It can be measured in terms of the partial vapor pressure of the soil water via the following equation:

$$\psi = \frac{RT}{v_w} \ln \frac{p_v}{p_{v0}} \quad (1)$$

where T is the absolute temperature, R is the universal gas constant, v_w is the molar volume of water, p_{v0} is the saturated vapour pressure at the temperature T , and p_v the pressure of the vapour in equilibrium with the soil water.

Whilst this definition is rigorous and correct, it creates an apparent dichotomy between saturated and unsaturated soils. It seems to suggest that, as soon as the soil desaturates, we need to abandon the intuitive concept of pore-water pressure and enter the exoteric world of thermodynamics.

The puzzle becomes even more intricate when suction is separated into a matric and an osmotic component:

- *Matric or capillary component of free energy.* In suction terms, it is the equivalent suction derived from the measurement of the partial pressure of the water vapor in equilibrium with the soil water, relative to the partial pressure of the water vapor in equilibrium with a solution identical in composition with the soil water.
- *Osmotic (or solute) component of free energy.* In suction terms, it is the equivalent suction derived from the measurement of the partial pressure of the water vapor in equilibrium with a solution identical in composition with the soil water, relative to the partial pressure of water vapor in equilibrium with free pure water.

In different words, matric suction is associated with the partial pressure of the water vapour in equilibrium with the water residing in the soil ideally free of solutes, whereas the osmotic suction is associated with the partial pressure of the water vapour in equilibrium with the soil water (including its solutes) isolated from the soil.

The final (and perhaps fatal) blow is struck when matric suction is eventually expressed in 'practical terms' as the difference between air-pressure and pore-water pressure, $u_a - u_w$, an operational definition oblivious of the 'grand' thermodynamical definition given above. These different definitions of suction, some of them built upon a thermodynamics background that civil engineers are generally not familiar with, make the first approach to unsaturated soil mechanics very challenging.

The first concept to demystify is that pore-water pressure in unsaturated soils is defined and measured exactly in the same way as saturated soils. The only difference is that pore-water pressure in unsaturated soils is negative, which makes its measurement more problematic. It is to overcome the difficulty of measuring pore-water pressure in the negative range that we have historically developed techniques for indirect measurement, that in turn require thermodynamics concepts for a correct interpretation of such measurements.

However, if instruments to measure negative pore-water pressure directly had been available since the early days (i.e., high-capacity tensiometers), no one would have ever defined suction thermodynamically and made a distinction between matric and osmotic components of suction. No one would have ever defined suction as the difference between air pressure and pore-water pressure, because we always operate with gauge pressures and take for granted that pressures are referenced to the atmospheric pressure. The definition of pore-water pressure is therefore the same in saturated and unsaturated soils, as well as its measurement as illustrated in **Figure 1**. The only difference is that the level of water in the piezometer is located above or below the point of measurement, in saturated or unsaturated soils respectively. To work with a positive variable, we often find it convenient to consider a variable named suction, defined as the opposite of the pore water pressure, $s = -u_w$.

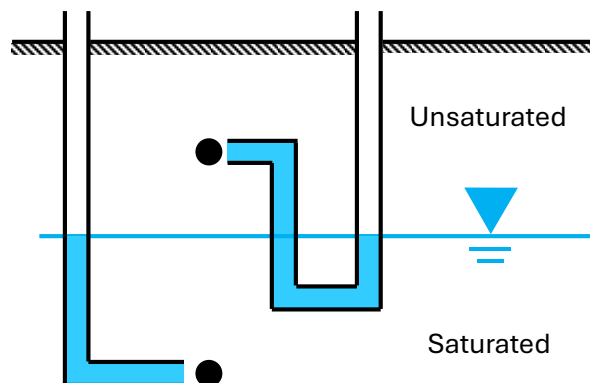


Figure 1. Pore-water pressure measurement below the groundwater table (saturated soil) and above the groundwater table (unsaturated soil)

Thermodynamically based definitions of suction only become important when we deal with indirect measurement techniques, but these are generally out of the scope of introductory undergraduate classes on unsaturated soil mechanics.

2.2 Effective stresses for unsaturated soils

A key concept in saturated soil mechanics is the effective stress σ' , defined as the difference between the total stress, σ , and the pore-water pressure, u_w ($\sigma' = \sigma - u_w$), and postulated to control all aspects of saturated soil mechanical behaviour.

When approaching the mechanics of unsaturated soils, it is natural to seek an equivalent concept to build constitutive relationships to model deformation and shear strength behaviour. However, lecturers approaching unsaturated soil mechanics are faced with a plethora of definitions considering either one single effective stress or two independent effective stresses (Table 1).

Table 1. Effective stress(es) for unsaturated soil behaviour (σ' =effective stress, σ =total stress, u_a =air pressure, u_w =pore-water pressure, χ =empirical function, S_r =degree of saturation, n =porosity, e =void ratio, e_w =water ratio, e_{wm} =microstructural water ratio)

• $\sigma' = \sigma - \chi(S_r) u_w$	Bishop (1959)	(2a)
• Net stress $\sigma - u_a$ • Matric suction ($u_a - u_w$)	Coleman (1962) Bishop & Blight (1963) Matyas & Radhakrishna (1968) Fredlund and Morgenstern (1977) Tarantino <i>et al.</i> (2000)	(2b)
• Average skeleton stress $\sigma - S_r u_w$ • Modified suction $n(-u_w)$	Houlsby (1997) Wheeler <i>et al.</i> (2003)	(2c)
• Average skeleton stress $\sigma - S_r u_w$ • Bonding stress suction $f(u_w)(1 - S_r)$	Gallipoli <i>et al.</i> (2003)	(2d)
Microstructurally based effective stress (elastic and shear strength behaviour) • $\sigma' = \sigma - \frac{e_w - e_{wm}}{e - e_{wm}} u_w$	Tarantino and Tombolato (2005) Alonso <i>et al.</i> (2010)	(2e)

This might be confusing but should not be surprising. Saturated soils are two-phase systems (solids and water) with the total stress and pore-water pressure acting on a soil element. These can be combined into a single saturated effective stress, i.e., only one of these two stresses is 'independent'.

Unsaturated soils are three-phase systems (solids, air, water) with the total stress, pore-water pressure, and air pressure acting on a soil element. If we reduce by one the number of independent variables (as is the case of saturated soils), we end up to two independent effective stresses governing unsaturated soil mechanical behaviour.

It is also not surprising that we can find different options for the pair of independent effective stresses if we recall the original statement of effective stress as formulated by Terzaghi (1936):

All the measurable effects of a change of the stress, such as compression, distortion and a change of the shearing resistance are exclusively due to changes in the effective stresses.

The term 'measurable' underlines the 'experimental' basis of the effective stress, and the use of a given pair of effective stresses becomes a matter of convenience provided they allow capturing experimental observations. It can be also expected that the choice of effective stress(es) is linked to the specific response to be modelled (e.g., elastic or shear strength behaviour).

The second concept to demystify is that soil mechanical behaviour is not controlled by a (single) effective stress. This happens for the case of soils that are fully saturated, but saturation is just one very peculiar saturation state ($S_r=1$) among all possible saturation states ($0 < S_r < 1$). The unsaturated soil and two effective stresses represent indeed the general case (Jommi, 2000).

The ‘experimental’ nature of the effective stress allows for the use of different effective stress(es) depending on the problem to be modelled. It is shown later in the paper that shear strength behaviour of unsaturated soils can be modelled using a single ‘unsaturated’ effective stress, similar to the classical ‘saturated’ effective stress. However, other problems involving soil deformation due to drying or wetting require two effective stresses (not discussed in this paper).

2.3 The false myth of conservativeness of saturated soil mechanics

Real life geotechnical problems often involve a groundwater table that lies below the ground surface, i.e., the upper portion of the soil profile above the groundwater table is characterised by negative pore-water pressures and degrees of saturation generally lower than unity (**Figure 2**). When teaching geotechnical design at the undergraduate level, it is often suggested to assume the pore-water pressure above the water table equal to zero (green profile in **Figure 2**). This assumption is referred to as ‘dry’ approach, because zero fluid pressures are the ones establishing in an ideally dry soil.

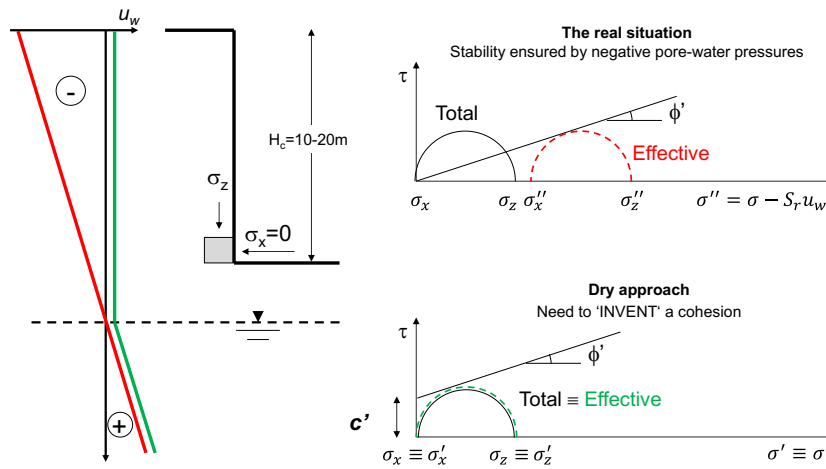


Figure 2. Stability of a vertical cut above the groundwater table: conventional ‘dry’ approach versus unsaturated soil mechanics analysis

The rationale behind this assumption is that it leads to conservative design. Let us consider the shear strength for the case of a saturated soil:

$$\tau = (\sigma - u_w) \tan \phi' + c' \quad (3)$$

where ϕ' is the effective angle of shearing resistance and c' is the effective cohesion. The pore-water pressure is negative above the ground water table ($u_w < 0$) and therefore gives a positive contribution to the shear strength. If neglected by assuming $u_w = 0$, this leads to underestimation of shear strength, i.e., a conservative assumption. However, there are cases where the ‘dry’ assumption leads to falsely conservative design.

Let us consider the vertical cut in a granular material above the ground water table (**Figure 2**). These excavations are often observed to be stable because of the effect of partial saturation (Stanier and Tarantino, 2013). The shear strength criterion for unsaturated granular materials can be written as follows (Tarantino and El Mountassir, 2013):

$$\tau = \underbrace{(\sigma - S_r u_w)}_{\sigma''} \tan \phi' + c' \quad (4)$$

where the term in brackets σ'' can be viewed as an effective stress valid for granular material shear strength. Because the pore-water pressure is negative, the effective stress Mohr circle for the soil element at the base of the excavation is shifted on the right-hand side with respect to the total stress Mohr circle, allowing for stable conditions.

If the same vertical cut is analysed by considering the conventional ‘dry’ assumption, the pore-water pressures are set equal to zero and the effective stress Mohr circle coincides with the total stress one. In this case, it is necessary to assume that the soil possesses an effective cohesion to make the vertical

cut stable and reconcile the analytical calculation with the observation in the field. This cohesion is not real. However, it will be assumed to be a soil property contributing to increasing shear strength even if negative pore-water pressure vanishes, for example due to rainwater infiltration. In this sense, the 'dry' assumption can be falsely conservative.

3 From elementary physical mechanisms to hydraulic and mechanical behaviour of unsaturated soils

3.1 Capillarity (Surface tension and contact angle)

The interface between air and water behaves like a membrane in tension and the uniform tension generated within the interface is named surface tension. A very simple experiment can demonstrate this membrane-like behaviour of the air-water interface. **Figure 3a** shows a paper clip that was gently placed on the water surface and remained on the surface supported by the air-water 'membrane' that stretched to counterbalance the paper clip self-weight. It is the surface tension acting tangentially to the air-water interface that sustains the paper clip. The counterproof is that, when pushed into the water, the paper clip sunk to the bottom of the container due to its higher density compared to water (**Figure 3b**).



(a)



(b)

Figure 3. Simple experiment to demonstrate water surface tension. (a) Paper clip 'floating' on membrane-like air-water interface. (b) Paper clip sunk at the bottom of the container.

This interface will curve in proximity of a solid surface to form a meniscus. If adhesive forces between solid and water prevail on cohesive forces in the water, the interface is concave towards the air and forms a contact angle θ lower than 90° with the solid surface. Contact angles lower than 90° are typical of soil water *on* soil minerals (**Figure 4**). The contact angle varies between a minimum and a maximum value, $0 < \theta_{\min} < \theta < \theta_{\max} < 90^\circ$. Menisci that are concave on the air side generate water pressures lower than the air pressure. Let us consider the equilibrium of the meniscus

$$u_w \cdot \pi \cdot \frac{d^2}{4} + T \cos \theta \cdot \pi \cdot d = u_a \cdot \pi \cdot \frac{d^2}{4} \quad (5)$$

where u_w is the water pressure at the back of the meniscus, u_a is the air pressure, T is the surface tension, θ is the contact angle, and d is the diameter of the capillary tube. The upward vertical component of the surface tension acting along the perimeter of the air-water-solid junction contributes to counterbalance the downward air pressure. We can derive the water pressure at the back of the meniscus by rearranging Eq. (5):

$$u_w - u_a = -\frac{4T \cos \theta}{d} = -\frac{2T \cos \theta}{r} = -\frac{2T}{R} \quad (6)$$

where R is the radius of curvature of the meniscus, and r is the radius of the capillary tube. If the contact angle is lower than 90° , the gauge water pressure $u_w - u_a$ is therefore negative.

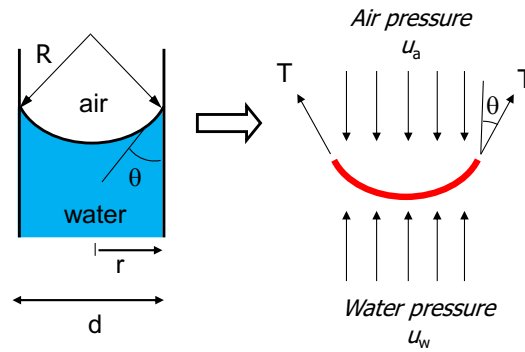


Figure 4. Equilibrium of the curved air-water interface and the generation of negative water pressures

It is instructive to quantify the minimum gauge pressures that can be sustained in capillary tubes having diameters of the same order of magnitude as the size of pores in clay, silt, and sand. For sake of simplicity, let us assume that pore size is about 1/6 of the grain size, which is approximately the size of the pore in a system of spheres in cubic packing, and contact angle is $\theta=0$. Eq. (6) shows that the minimum pressure varies by one order of magnitude from sand to silt to clay (Table 2). A very simple day-to-day experience shows that pressure is higher on the concave side and lower on the convex side of a curved membrane. **Figure 5** shows a balloon with the inner pressure (on the concave side of the membrane) greater than the outer pressure (on the convex side).

Table 2. Order of magnitude of minimum negative pressure generated in sand, silt, and clay

	Sand	Silt	Clay
$d_{\text{grain}} (\mu\text{m})$	200	20	2
$d_{\text{pore}} (\mu\text{m})$	30	3	0.3
$u_w - u_a$ (kPa)	-10	-100	-1000



Figure 5. Air pressure on the concave side of a membrane in tension is greater than pressure on the convex side (as is the case of air and water pressures on the two sides of the meniscus)

3.2 Capillary rise

The equilibrium in Figure 4 and Eq. (6) shows that the water pressure at the back of a curved air-water interface (meniscus) is negative. This allows revisiting the topic of capillary rise which undergraduate students are likely to have covered in their hydraulics classes. Consider a capillary tube immersed in water (Stage 1, **Figure 6**). The presence of the solid wall causes the air-water interface to bend (Stage 2, **Figure 6**), in turn generating a negative water pressure at the back of the meniscus. The lower water pressure in the capillary tube causes an upward water flow inside the capillary tube, until hydrostatic conditions are restored (Stage 3, **Figure 6**).

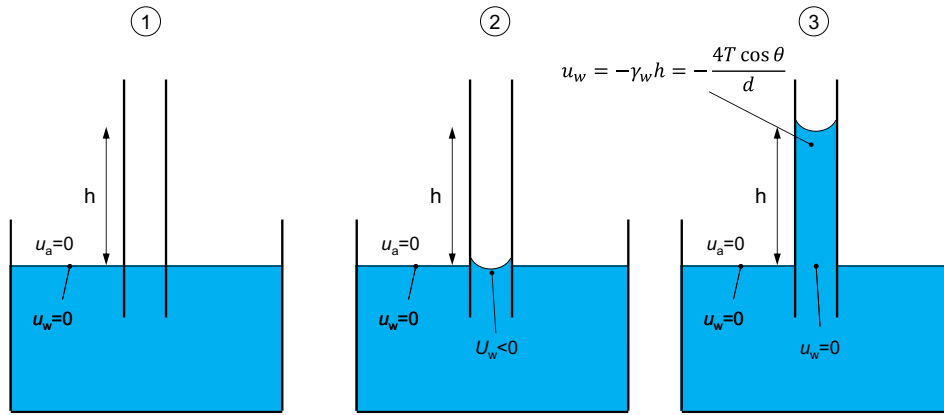


Figure 6. Capillary rise revisited considering the dynamic process leading to final equilibrium state

The capillary rise is proportional to the negative pressure at the back of the meniscus, which is in turn inversely proportional to the diameter of the capillary tube according to Eq. (6). Figure 7 shows an experiment that can be easily reproduced in the class to demonstrate how capillary rise increases as the diameter of the capillary tube reduces (6).

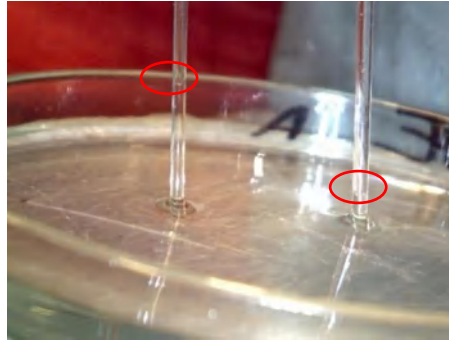


Figure 7. Example of capillary rise inversely proportional to the diameter of the capillary tube

3.3 Water retention behaviour via capillary tubes

Consider the case of a single capillary tube connected to a reservoir, initially located at the top of the capillary tube (Stage 1, **Figure 8**). If the reservoir is lowered, the pressure at the back of the meniscus becomes negative (Stage 2, **Figure 8**). This negative pressure can be sustained by the meniscus thanks to the increase in its radius of curvature R , i.e. a decrease of the contact angle θ .

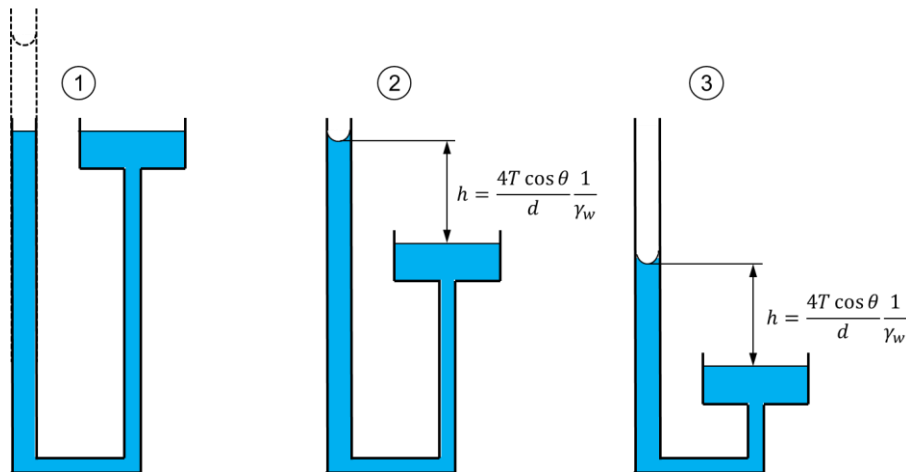


Figure 8. Emptying of a capillary tube subjected to negative pressures

However, there is a limit to the decrease of the contact angle, as it cannot attain values lower than θ_{min} . Such a limit is reached when the distance of the reservoir from the top of the capillary tube is equal to the capillary rise. If the reservoir is further lowered, the meniscus will move down accordingly, to maintain the distance between the meniscus and the reservoir no greater than the capillary rise (Stage 3, **Figure 8**).

Consider now a system of capillary tubes of different diameter connected to a reservoir (**Figure 9**). This system of capillary tubes mimics the system of pores in a soil. Let us consider the case where the length of the capillary tubes is lower than the capillary rise, i.e., all tubes are filled with water and the capillary system is fully saturated (Stage 1, **Figure 9**).

If the reservoir is lowered, the meniscus will first lower in the tube with the larger diameter, as the capillary rise height is lower in the tube with larger diameter (Stage 2, **Figure 9**). In this stage, the smaller diameter tubes will initially remain water filled.

If the reservoir is further lowered down, the meniscus in the larger capillary tube will follow the reservoir and a second tube will start emptying (Stage 3, **Figure 9**). As the reservoir moves downward, there will be a stage where the distance of the reservoir from the base of the capillary tubes exceeds the capillary rise of the tube with larger diameter, which will become empty (Stage 4, **Figure 9**).

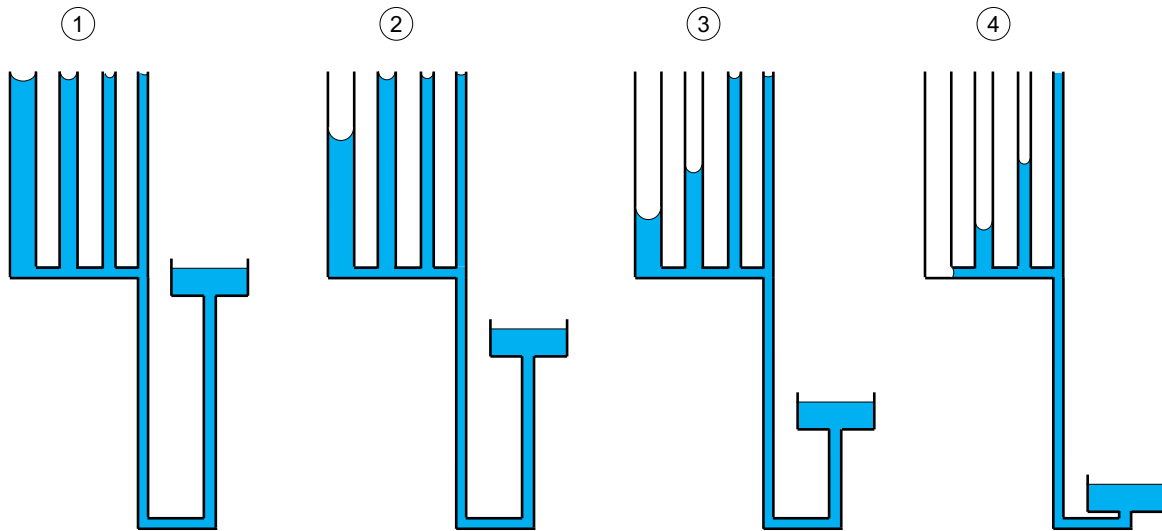


Figure 9. Emptying of a system of capillary tubes subjected to negative pressures

Let us plot the negative pressure (or suction) on the horizontal axis and the degree of saturation of the system of capillary tubes on the vertical axis (**Figure 10**). The relationship between suction and degree of saturation is the one shown by the continuous curve in **Figure 10**, which is referred to as 'Water Retention Curve (WRC)'.

The WRC for the capillary system in **Figure 10** accurately mimics the WRC measured experimentally in soils. There is a value of suction that marks the desaturation of the soil, which is referred to as air-entry suction, s_{AE} . The air-entry suction is associated with the larger pore size and the order of magnitude of s_{AE} in sands, silts, and clays can be derived from **Table 2**, being 10, 100, and 1000 kPa respectively.

The decay of degree of saturation beyond the air-entry suction depends on the gradation of the pore size. Let us consider the case of capillary tubes having all the same diameter of the larger tube in **Figure 10**. Beyond the air entry suction, all tubes will empty simultaneously, and the system will become dry much earlier than the well-graded capillary system shown in **Figure 10**. In other words, the more uniform is the distribution of the pores (i.e., the more uniform is the particle size distribution), the steeper is the water retention curve beyond the air-entry point.

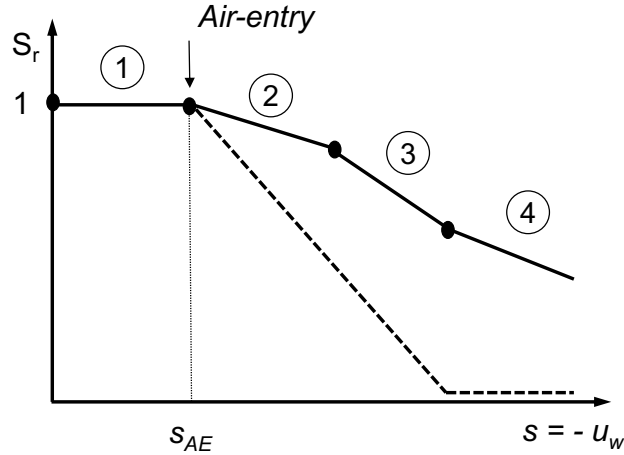


Figure 10. Water retention curve in a system of capillary tubes (dashed curve show the case of a system of capillary tubes having the same size)

3.4 Mechanical behaviour via particle scale interactions

Figure 11 shows the distribution of water in an unsaturated soil. Water can entirely fill sub-regions, referred to as 'bulk water' (or 'funicular' regime). In these sub-regions the interparticle contacts are fully saturated. Water can also form menisci at the interparticle contact, referred to as 'meniscus water' (or 'pendular' regime).

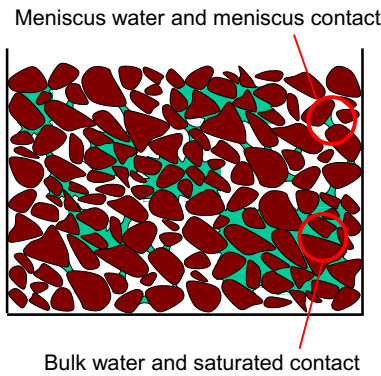


Figure 11. Bulk and meniscus water in an unsaturated soil

At the interparticle contact, the air-water interface forms a surface known as Plateau nodoide. However, little error is introduced if the meridian curve is assumed to be circular with radius c (Figure 12). The radii b and c of the meniscus depends on the angle β defining the position of the meniscus junction and the particle radius r .

$$c = r \left(\frac{1}{\cos \beta} - 1 \right); \quad b = r \left(1 + \tan \beta - \frac{1}{\cos \beta} \right) \quad (7)$$

The pressure difference across the liquid interface, $s = u_a - u_w$, also depends on the radii b and c of the meniscus (Figure 12).

$$s = u_a - u_w = -T \left(\frac{1}{c} - \frac{1}{b} \right) \quad (8)$$

The smaller is the angle β , the smaller is the volume occupied by the meniscus water, and the higher is the suction s . For $\beta < 53^\circ$, the pore-water pressure u_w is negative (lower than atmospheric air pressure, u_a).

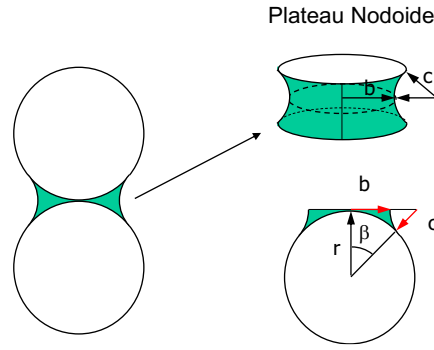


Figure 12. Capillary water at the interparticle contact (meniscus contact)

Figure 13a shows the equilibrium of the forces at the interparticle ‘meniscus’ contact, resolved to derive the intergranular stress, σ_i :

$$\sigma_i = \frac{N}{A} = (\sigma - u_a) + \underbrace{(u_a - u_w) \frac{A_w}{A} - T \frac{P_w}{A_w}}_{\sigma_i^m} \quad (9)$$

where N is the intergranular force, A is the total contact area, A_w is the wetted area, and P_w is the wetted perimeter.

The first term on the right-hand side of Eq. (9) accounts for the effect of the external total stress, σ . The second term accounts for the compressive intergranular stress generated by the negative pore-water pressure, and the third term accounts for the compressive intergranular stress generated by the surface tension T . The second and third term grouped together account for the compressive intergranular stress generated by the meniscus, σ_i^m .

It can be demonstrated mathematically that σ_i^m does not change significantly with suction ($\sigma_i^m \cong$ constant). This is intuitive, because as the angle β decreases, suction $s = u_a - u_w$ increase but the wetted area A_w decreases. As a result, σ_i^m remains essentially constant.

The compressive force generated by the meniscus can be demonstrated by a simple experiment. **Figure 14** shows a glass bead ‘attached’ to the bottom of a Petri dish. Although not visible, there is a meniscus at the contact between the bead and the dish, similar to the one in **Figure 12**, to generate the compressive force that outweighs the gravity force acting on the bead.

Figure 13b shows the equilibrium of the forces at the interparticle ‘saturated’ contact, again resolved to derive the intergranular stress, σ_i :

$$\sigma_i = \frac{N}{A} = \sigma - u_w = \sigma + \underbrace{s}_{\sigma_i^b} \quad (10)$$

The bulk water contributes to the intergranular stress via the suction, i.e., $\sigma_i^b = s$. The intergranular stress takes the form of the ‘saturated’ Terzaghi’s effective stress. It should be noted that the intergranular stress, σ_i , is fundamentally different from the effective stress σ' , as demonstrated conceptually and experimentally by Skempton (1960). The assumption $\sigma_i \cong \sigma'$ is very convenient here, as it allows a simple development of a shear strength criterion for unsaturated soils. If the intergranular stress is assumed to control the shear strength similarly to the saturated effective stress, we can write:

$$\tau = \sigma_i \tan \phi' \quad (11)$$

where ϕ' is the effective angle of shearing resistance.

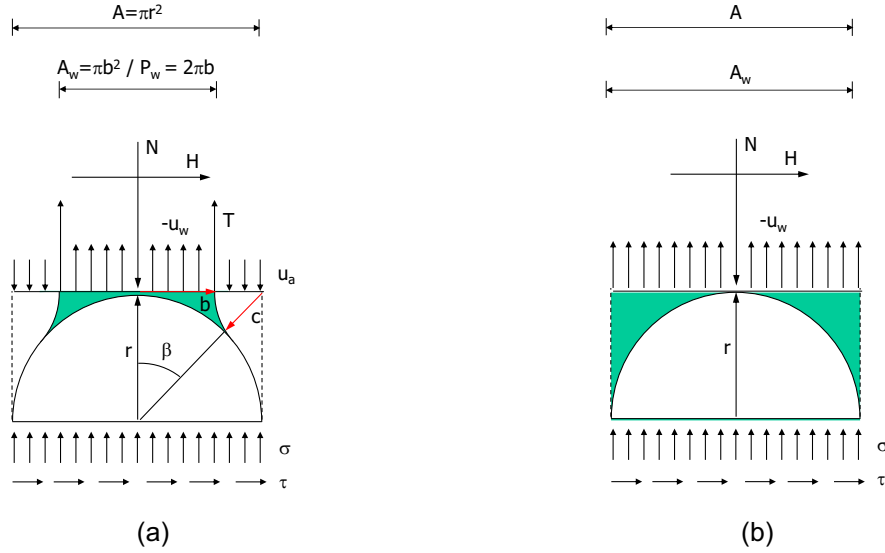


Figure 13. Intergranular stress. (a) Meniscus at the interparticle contact. (b) 'Saturated' contact



Figure 14. Glass bead 0.5 mm size 'attached' to the bottom of a Petri dish by capillary forces

Figure 15 shows an idealised assembly of particles subjected to shearing. The intergranular stress is the weighted average of the intergranular stresses at the saturated and meniscus contacts. For the case of saturated soil (suction lower than the air-entry suction, **Figure 15a**) and considering Eq. (10), we have:

$$\tau = \sigma_i \tan \phi' = \sigma \tan \phi' + s \tan \phi' \quad (12)$$

For the case of a partially saturated soil at high/medium degrees of saturation (**Figure 15b**) and considering Eqs. (9) and (10), we can write:

$$\tau = \sigma_i \tan \phi' = \sigma \tan \phi' + \left(\frac{V_{bw}}{v_v} \sigma_i^b + \frac{V_{mw}}{v_v} \sigma_i^m \right) \tan \phi' \quad (13)$$

where V_v is the volume of voids, V_{vb} is the fraction of the void volume occupied by the bulk water, and V_{vm} is the fraction of the void volume occupied by meniscus water. Since in the high/medium range of degrees of saturation $V_{vb} \ll V_{vm}$, we can simplify Eq (13) as follows:

$$\tau = \sigma_i \tan \phi' \cong \sigma \tan \phi' + \left(\frac{V_{bw}}{v_v} \sigma_i^b \right) \tan \phi' \cong \sigma \tan \phi' + (S_r s) \tan \phi' \quad (14)$$

For the case of a partially saturated soil at medium/low degrees of saturation (**Figure 15c**) and considering Eqs. (9), we can write:

$$\tau = \sigma_i \tan \phi' = \sigma \tan \phi' + (\sigma_i^m) \tan \phi' = \sigma \tan \phi' + \text{constant} \quad (15)$$

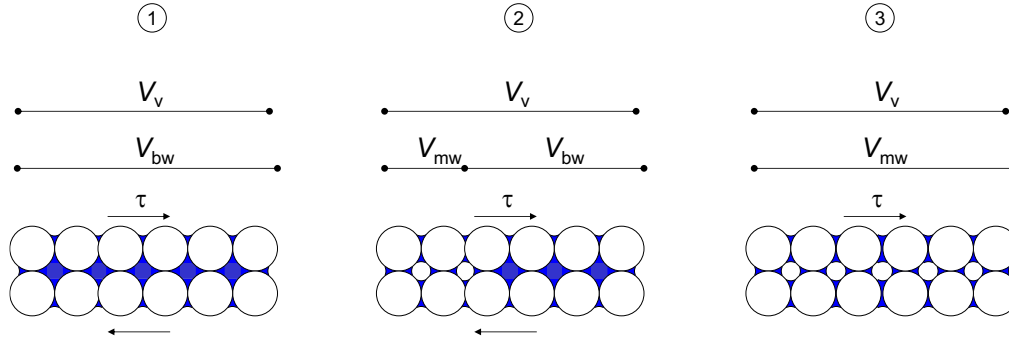


Figure 15. Intergranular normal stress in presence of bulk water (V_{bw}) and meniscus water (V_{mw})

The effect of suction on shear strength is summarised in **Figure 16**. In the range from saturation to medium degree of saturation shown by the continuous curve, the shear strength criterion can be formulated according to Eqs. (12) and (14):

$$\tau = \sigma \tan \phi' + (S_r s) \tan \phi' = \frac{(\sigma + S_r s)}{\sigma''} \tan \phi' \quad (16)$$

This criterion has been demonstrated to hold experimentally for granular soils (sandy and silty geomaterials) by Tarantino and El Mountassir (2013). The stress σ'' can be viewed as an unsaturated effective stress than can be used limited to shear strength of granular materials.

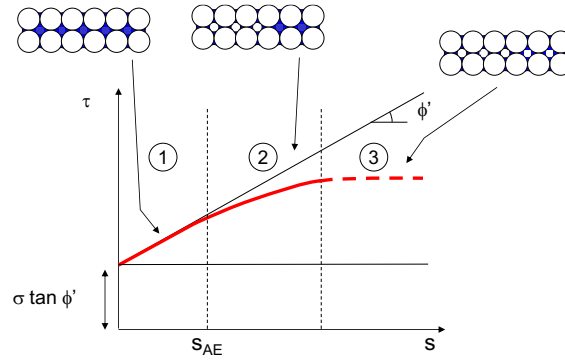


Figure 16. Effect of suction on shear strength at varying degrees of saturation

For the case of clays, we can assume that microscale mechanical interactions involve clay aggregates instead of sand/silt particles. In this case, only the water in the pore space between the aggregates contributes to shear strength (Tarantino and Tombolato, 2005; Alonso *et al.*, 2010). The shear strength criterion therefore modifies as follows:

$$\tau = \left[\sigma + \left(\frac{e_w - e_{wm}}{e - e_{wm}} \right) s \right] \tan \phi' \quad (17)$$

where e is void ratio, e_w is the water ratio and e_{wm} is the microstructural water ratio, i.e., the mass of water within the clay aggregates per unit mass of solids not contributing to shear strength. The term in round brackets, S_{rM} , represents the degree of saturation of the water between the aggregates (inter-aggregate), i.e., the degree of saturation derived by excluding the water within the aggregates.

Although the shear strength criterion for clays given by Eq. (17) is an intuitive extension of the criterion for granular materials, it poses the practical problem of the experimental determination of the microstructural water ratio, e_{wm} . This requires unsaturated shear testing with equipment enabled for suction control or monitoring, not available in commercial laboratories and the majority of research laboratories.

To bypass this problem, one can adopt the simplified criterion shown in **Figure 17** (red envelope), which assumes a constant shear strength beyond the air-entry suction, set equal to the value attained at the air-entry suction:

$$\tau = \sigma \tan \phi' + c_{unsat} \quad [c_{unsat} = s_{AE} \tan \phi'] \quad (18)$$

Values of c_{unsat} , though conservative, are generally high enough to make a difference in stability analyses. For example, $c_{unsat} = 182$ kPa for the case of $s_{AE} = 500$ kPa and $\phi' = 20^\circ$. The advantage of using Eq. (18) is that it only requires information about the air-entry suction in addition to the saturated shear strength parameters.

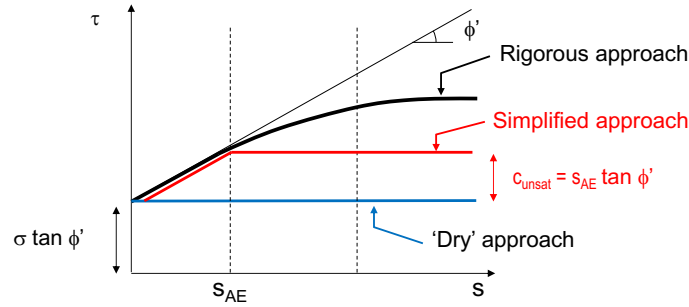


Figure 17. Simplified shear strength criterion for clays

4 Quantitative preliminary analysis of routine engineering problems

The applications presented in this section are aimed to demonstrate how taking into account unsaturated soil behaviour can affect the result of a stability analysis compared to the traditional 'dry' approach. The first application shows the stability analysis of a vertical cut in a silt (Stanier and Tarantino, 2013), while the second presents a classic slope stability problem using Bishop's method of slices (Bishop, 1955). For the scope of this paper, in both problems the suction profile distribution has been assumed as hydrostatic, although the same approach can be extended to any suction profile distribution. Simplified models for the shear strength criterion presented in Section 3 have been adopted. For the sake of consistency, the failure criterion has been expressed with Eq. (18) for all soils, with c_{unsat} defined as follows:

$$\text{For granular materials (sands and silts), } c_{unsat} = s S_r \tan \phi' \quad (19)$$

$$\text{For clays, } c_{unsat} = \begin{cases} s \tan \phi' & \text{for } s < s_{AE} \\ s_{AE} \tan \phi' & \text{for } s > s_{AE} \end{cases} \quad (20)$$

Keeping this notation has two advantages. The first is that it presents the failure criterion in a format that students are already familiar with, i.e. with a term depending on effective stress and a term presented as cohesion, even though it is not necessarily constant. This also allows implementing this failure criterion in geotechnical engineering software that is not designed to account for unsaturated shear strength in the first place. By dividing a soil layer in an appropriate number of sublayers, a value of cohesion corresponding to c_{unsat} depending on average suction in each sublayer can be attributed to the soil, thus including the contribution of unsaturated shear strength.

4.1 Excavation (vertical cut)

In the traditional 'dry' approach, where pore water pressure is assumed to be equal to zero above the phreatic surface, effective stresses correspond to total stresses. This results in the Mohr's circle of stresses intersecting the failure envelope for any height of the vertical cut, leading to a value of critical height equal to zero, which is of course not supported by experimental evidence (including sandcastles!). The lower and upper bound theorems of plasticity are applied here to analyse the stability of a vertical cut in silt with height H equal to 3 m, assuming a depth of water table z_w equal to 15 m, according to the geometry shown in **Figure 18**. This results in a value of suction equal to 120 kPa at the base of the cut,

having assumed 10 kN/m^3 for the unit weight of water. The material properties of the silt are reported in **Table 3**.

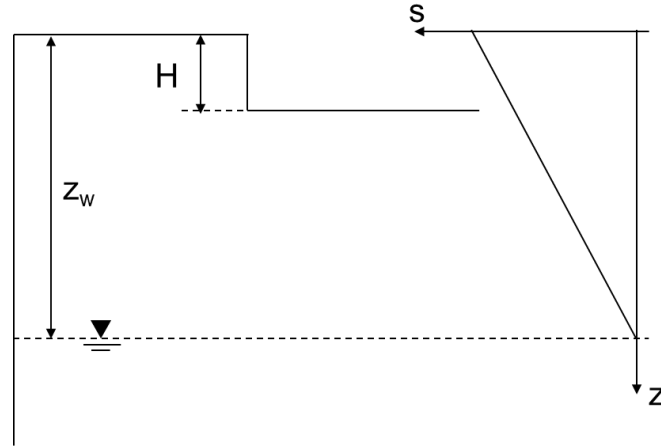


Figure 18. Vertical cut and hydrostatic suction distribution

Table 3. Material properties

	Sand	Silt	Clay
Friction angle ϕ' [°]	35	26	20
Unit weight γ [kN/m ³]	18	19	20
Air entry suction s_{AE} [kPa]	10	100	1000

Lower bound theorem

Assuming the vertical and horizontal as principal directions, at any depth z the total vertical stress σ_v and total horizontal stress σ_h at equilibrium are given by:

$$\sigma_v = \gamma z \quad (21)$$

$$\sigma_h = 0 \quad (22)$$

where γ is the unit weight of the soil. By imposing that the Mohr circle in the plane does not violate the failure criterion, the minimum allowable horizontal total stress can be calculated as:

$$\sigma_{h,min} = k_a \sigma_v - 2c_{unsat} \sqrt{k_a} \quad (23)$$

where k_a is the active earth pressure coefficient equal to

$$k_a = \frac{(1 - \sin \phi')}{(1 + \sin \phi')} = 0.390 \quad (24)$$

and c_{unsat} is calculated as shown in Eq. (19). The degree of saturation S_r is obtained from the simplified water retention curve shown in **Figure 19**.

The calculated value of $\sigma_{h,min}$ is -47.1 kPa , which is lower than the horizontal stress at equilibrium (Eq. (22)), therefore the vertical cut is stable.

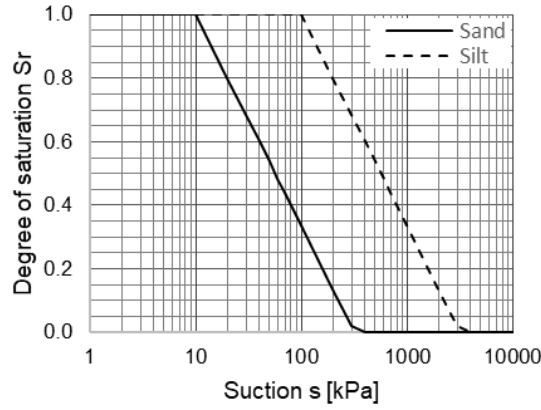


Figure 19. Simplified water retention curves for sand and silt

Upper bound theorem

A kinematic mechanism consisting of a single block with a planar slip surface inclined by an angle $\alpha = \pi/4 - \phi'/2$ is considered for the application of the upper bound theorem of plasticity (Figure 20).

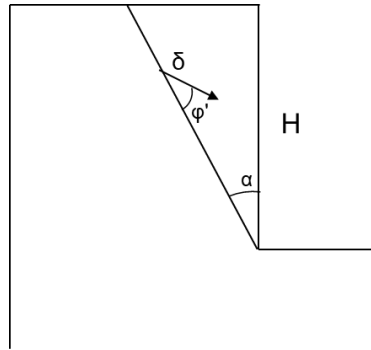


Figure 20. Kinematic mechanism with single block sliding on planar surface

The work done by the external forces W_e is calculated as

$$W_e = W \delta_v \quad (25)$$

where W is the weight of the block calculated as

$$W = \frac{1}{2} \gamma H^2 \tan \alpha \quad (26)$$

and δ_v is the vertical component of the block displacement calculated as

$$\delta_v = \delta \cos(\alpha + \phi') \quad (27)$$

The work done by the internal forces W_i is calculated as

$$W_i = c_{unsat} \delta_t L \quad (28)$$

where δ_t is the component of the block displacement parallel to the slip surface calculated as

$$\delta_t = \delta \cos \phi' \quad (29)$$

and L is the length of the slip surface calculated as

$$L = \frac{H}{\cos \alpha} \quad (30)$$

This results in an external work equal to $W_e = 28.3 \text{ kN/m} \times \delta$ and an internal work equal to $W_i = 84.6 \text{ kN/m} \times \delta$, therefore the vertical cut is stable.

Simplified shear strength criterion

If the water retention curve is not available, as may often be the case in practice, a reasonable estimate can still be obtained using the simplified shear strength criterion shown in Eq. (18), even for silty or sandy soils. As an example, let us apply the lower bound and upper bound theorems of plasticity to the same vertical cut and let us calculate c_{unsat} as shown in Eq. (20).

When applying the lower bound theorem, this results in a value of $\sigma_{h,min}$ equal to -38.7 kPa, which is not too dissimilar from the value obtained from the rigorous shear strength criterion and is still lower than the horizontal stress at equilibrium (Eq. (22)), therefore proving again the stability of the vertical cut. When applying the upper bound theorem, the only term affected by c_{unsat} is the work of internal forces W_i (Eq. (28)), which becomes $W_i = 74.4 \text{ kN/m} \times \delta$. Once again this is greater than the external work, proving that the vertical cut is stable.

4.2 Slope stability analysis

Bishop's method of slices, which is typically covered in undergraduate geotechnical engineering courses, is used to analyse the stability of an ideal slope having the geometry illustrated in **Figure 21**, with the height $H = 5 \text{ m}$ and the width $W = 8 \text{ m}$ resulting in a slope angle of 32° . Only one slip surface is taken into account, as shown in the figure, with the soil mass divided in 8 slices. A depth of the water table equal to $z_w = 7 \text{ m}$ from the crest of the slope (i.e. 2 m from the toe of the slope) is considered, resulting in a suction value at the base of the slices ranging between 15 and 55 kPa.

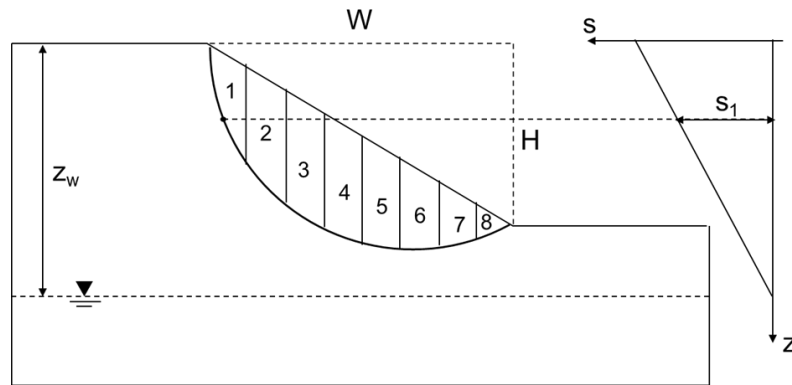


Figure 21. Ideal slope with 8 slices and hydrostatic suction distribution

The factor of safety F_s is hand calculated as shown below:

$$F_s = \frac{\sum (c_{unsat,i} b + W_i \tan \phi') \frac{1}{m_i}}{\sum W_i \sin \alpha_i} \quad (31)$$

where

$$m_i = \cos \alpha_i \left(1 + \frac{\tan \alpha_i \tan \phi'}{F_s} \right) \quad (32)$$

where W_i is the weight of each slice, calculated as the soil's unit weight multiplied by the slice area, and α_i is the inclination at the base of each slice measured from the drawing. The calculation of F_s requires an iterative procedure in two steps:

1. Assume an initial value of the factor of safety F_s in order to calculate the value of m_i for each slice (Eq. (32));
2. Insert the calculated values of m_i into the right-hand side of Eq. (31) in order to calculate the Factor of Safety F_s .

If the difference between the assumed and calculated F_s values is greater than 0.01 then further iterations are needed; otherwise the calculated value is considered to be the result of the analysis.

Calculations have been carried out considering two slopes made of two different materials, respectively a clay and a sand. For the clay, the only parameter required to calculate the term c_{unsat} is the air entry value s_{AE} , assumed equal to 1000 kPa, while for the sand the water retention curve is also required in order to calculate the degree of saturation at the base of each slice, as per Eq. (19). The water retention curve assumed for the sand is shown in **Figure 19**. Results are summarised in **Table 4**. As expected, the contribution of suction to the shear strength of the soil significantly increases the Factor of Safety in both slopes.

Table 4. Results of stability analyses

	F_s - Dry	F_s - Unsaturated
Sandy slope	1.88	3.15
Clayey slope	0.98	1.88

5 Conclusions

The paper has presented an innovative approach to introduce teaching of unsaturated soil mechanics in an undergraduate course. The main feature of this approach consists in deriving the hydraulic and mechanical models from elementary physical mechanisms. This makes the approach easy to implement by academics who don't pursue any research in the area of unsaturated soil mechanics and may not be experts in this field. The introduction of these concepts to students is supported by the use of small-scale, real-time experiments which can easily be carried out in a classroom setting. These experiments do not require the use of any advanced testing equipment, on the contrary, by using everyday objects they highlight how some of these mechanisms may even be observed in simple day-to-day experiences. This helps students develop a deeper understanding of the fundamentals of unsaturated soil mechanics while at the same time enhancing their engagement.

The presented approach also aims to enable students to carry out simple analyses by introducing unsaturated soil mechanics models in the framework of analysis methods that are typically included in undergraduate geotechnical engineering courses and therefore already familiar to students. These preliminary analyses require no more effort or time compared to analyses done under the traditional 'dry' assumption, but clearly highlight the impact of unsaturated soil behaviour on stability problems. Even though they may not provide the most accurate results in terms of stability analyses, the aim of these quantitative tools is to encourage students to critically analyse the results of their computations and gradually refine their engineering judgement, so that they can progress towards making independent decisions about whether more advanced analyses may be beneficial.

References

- Alonso, E., Pereira, J.-M. Vaunat, J., Olivella, S. (2010). A microstructurally based effective stress for unsaturated soils. *Géotechnique*, 60, pp. 913-925. DOI: 10.1680/geot.8.P.002.
- Bishop, A. W. (1955). The use of the slip circle in the stability analysis of slopes. *Géotechnique*, 5(1), pp. 7-17.
- Bishop, A. W. (1959). The principle of effective stress. *Teknisk Ukeblad*, 39, pp. 859-863.
- Bishop, A. W., Blight, G. E. (1963). Some aspects of effective stress in saturated and partly saturated soils. *Géotechnique*, 13(3), pp. 177-197.
- Coleman, J.D. (1962). Stress/strain relations for partly saturated soil. *Géotechnique*, 12(4), pp. 348-350.
- Fredlund, D., Rahardjo, H. (1993). *Soil Mechanics for Unsaturated Soils*, John Wiley & Sons, Inc., Hoboken, New Jersey, USA.
- Fredlund, D. G., Morgenstern, N. R. (1977). Stress state variables for unsaturated soils. *ASCE Journal of Geotechnical Engineering*, 103(5), pp. 447-466.
- Gallipoli, D., Gens, A., Sharma, R., Vaunat, J. (2003). An elastoplastic model for unsaturated soil incorporating the effects of suction and degree of saturation on mechanical behaviour. *Géotechnique*, 53, pp. 123-135. DOI: 10.1680/geot.53.1.123.37251.

- Houlsby, G. T. (1997). The work input to an unsaturated granular material. *Géotechnique*, 47(1), pp. 193–196.
- Jommi, C. (2000). Remarks on constitutive modelling of unsaturated soils. In: *Experimental evidence and theoretical approaches in unsaturated soils*, Proc. of Int. Workshop on Unsaturated Soil, Trento, Italy, Balkema, Rotterdam, pp. 139–153.
- Matyas, E. L., Radhakrishna, H. S. (1968). Volume change characteristics of partially saturated soils. *Géotechnique*, 18(4), pp. 432–448.
- Pantazidou, M., Houston, S., McCartney, J., Tarantino, A., Bardanis, M. (2024). Alert soil mechanics instructors of the main unsaturated soil issues: what and how to teach when experts disagree. *Proceedings of the XVIII ECSMGE 2024*, 26-30 August 2024, Lisbon, Portugal. DOI: 10.1201/9781003431749-120.
- Skempton, A. W. (1960). Effective stress in soils, concrete and rock. *Conference on Pore Pressure and Suction in Soils*, Butterworths, pp. 4-16.
- Stanier, S., Tarantino, A. (2013). An approach for predicting the stability of vertical cuts in cohesionless soils above the water table. *Engineering Geology*, 158, pp. 98–108. DOI: 10.1016/j.enggeo.2013.03.012.
- Tarantino, A., Mongioli, L., Bosco, G. (2000). An experimental investigation on the independent isotropic stress variables for unsaturated soils. *Géotechnique*, 50, pp. 275–282. DOI: 10.1680/geot.2000.50.3.275.
- Tarantino, A., Tombolato, S. (2005). Coupling of hydraulic and mechanical behavior in unsaturated compacted clay. *Géotechnique*, 55, pp. 307–317. DOI: 10.1680/geot.2005.55.4.307.
- Tarantino, A., El Mountassir, G. (2013). Making unsaturated soil mechanics accessible for engineers: Preliminary hydraulic–mechanical characterisation & stability assessment. *Engineering Geology*, 165, pp. 89–104. DOI: <https://doi.org/10.1016/j.enggeo.2013.05.025>.
- Terzaghi, K. (1936). The shearing resistance of saturated soils and the angle between the planes of shear. *Proc. 1st Int. Conf. Soil Mech. Found. Eng.*, 1, pp. 54–56.
- Wheeler, S. J., Sharma, R. S., Buisson, M. S. R. (2003). Coupling of hydraulic hysteresis and stress–strain behaviour in unsaturated soils. *Géotechnique*, 53(1), pp. 41–54.

Authors' bios

Alessia Amabile, University of Strathclyde (Scotland, UK)

Alessia Amabile is a Teaching Fellow in geotechnical engineering at the University of Strathclyde in Glasgow, Scotland. She graduated in civil engineering from the University of Naples Federico II and completed her PhD at the University of Strathclyde in 2018. Her disciplinary research interests involve the stability of flood embankments, including probabilistic methods for stability analyses and the use of field monitoring, numerical modelling and geophysical methods to characterise soil hydro-mechanical models in the saturated and unsaturated zone. In more recent years her research activity has focused on engineering education, in particular on the development of virtual and hybrid laboratories for civil engineering students at undergraduate level. Her research interests also include student feedback practices, especially in the context of large classes, and student experience enhancement.

Alessandro Tarantino, University of Strathclyde (Scotland, UK)

Alessandro Tarantino is Professor of Experimental Geomechanics at the University of Strathclyde in Glasgow, Scotland. His current research interests include the direct measurement of water tension in soils and plants, micromechanical behaviour of saturated and unsaturated clays, soil-plant-atmosphere interaction, and stability of natural and engineered slopes subjected to rainwater and floodwater infiltration. He has led major European consortium research projects including the Marie Curie European Training Network 'TERRE' (Training Engineers and Researchers to Rethink geotechnical Engineering for a low carbon future, 2015–2019). He is co-editor of the books 'Advanced Experimental Unsaturated

Soil Mechanics' (2005) and 'Laboratory and Field Testing of Unsaturated Soils' (2009). He has been keynote/theme lecturer at numerous International Conferences (the 8th International Conference on Unsaturated Soils in 2023 and the ICE Géotechnique Lecture in October 2023 the most recent ones).

Teaching numerical methods or teaching with numerical methods?

F. Ceccato

University of Padua, Padua, Italy
francesca.ceccato.1@unipd.it

ABSTRACT: This paper presents some of the results of a collaboration between TC103 (numerical methods) and TC306 (geoengineering education) of ISSMGE with the objective of producing high quality educational material to be shared with educators in form of figures or videos. The project stems from the idea that figures, charts and videos obtained with the use of numerical tools can enrich teaching of key concepts of geomechanics in introductory courses. Examples are visual resources obtained using DEM to illustrate micro-phenomena and the particulate nature of soils and its consequences, or using FEM/FDM to illustrate macro-phenomena such as stresses under loaded areas or bearing capacity of a foundation. Figures are submitted with metadata useful to guide the use of the material even by educators that are not experts in numerical methods. However, this raises a fundamental question: how detailed should be student's (and educator's) knowledge on numerical methods to fully understand (and use) the material? This paper discusses this issue showing how the same material, if correctly prepared, can be used with different purposes both in base and advanced courses. Pilot examples are illustrated with specific emphasis on stress under loaded areas.

Keywords: Numerical Methods, Stress bulbs, Stress visualization, FEM

1 Introduction

Figures and videos are essential to explain fundamental concepts of soil mechanics. YouTube seems to abound of educational videos and a number of websites shares figures, Power Point slides and web-app for students. However, a recent study revealed that the majority of teachers in geotechnical engineering are not satisfied with this educational material (Pantazidou & Calvello, 2023). The survey revealed that 52% of instructors were not satisfied with the materials they currently used, and 45% were not satisfied with materials found through searches on the web. Respondents expressed a significant need for materials to be used both in lectures and to engage students outside class, with case studies and laboratory-related materials being the most desired, but there is also a significant desire of photographs and videos. While no one topic stood out clearly above all others, educational material for foundation topics, particularly bearing capacity and stress distribution underneath loaded areas, will be useful to a good percentage of geotechnical engineering instructors.

Building on this, a collaborative initiative was launched between ISSMGE (International Society for Soil Mechanics and Geotechnical Engineering) technical committees TC306 on Geoengineering Education and TC103 on Numerical Methods to address these gaps, with the objective of developing peer-reviewed, high quality, and sharable educational material by means of numerical methods. Specifically, numerical methods, such as the Discrete Element Method (DEM), Finite Element Method (FEM), and Material Point Method (MPM), may be used to create short videos, animations, effective figures or hands-on spreadsheets to help visualize complex concepts and enhance student understanding. All the material will be prepared with accompanying metadata and usage guidelines to ensure clarity and usability. These resources will guide instructors, especially those unfamiliar with numerical methods, how to effectively incorporate the materials into their teaching.

This initiative brings a fundamental question: can we use this material without knowing and teaching the basics of these numerical methods? In base courses, numerical methods can be used as

complementary tools to enhance students' understanding of fundamental concepts through improved visualizations, which requires only a very limited knowledge of the mathematical details of the applied numerical method. The accompanying metadata will support instructors in this process. In advanced courses, the teacher can discuss with more details the features of the models and provide assignments that require the implementation or modification of the model. In both cases, it should be avoided to present numerical methods as replacements for established theories and methods.

A preliminary survey within the members of TC103 and TC306 explored the availability of ready-to-use material that could be immediately shared, but many instructors indicated that they had prepared Excel files or scripts for their classes, but admitted that these were not ready to be shared or used by others. This confirms the private nature of teaching, and that we are still struggling to create an engaged community of teachers who publicize their educational material and take the responsibility of judging the educational material of their colleagues.

Another notable feature of this initiative is the introduction of a formal peer-review phase, novelty in this context. Additionally, the reviewed and finalized materials will be shared on the ISSMGE platform dedicated to peer-reviewed educational resources (<https://www.issmge.org/education/peer-reviewed-educational-materials>), marking a significant step toward elevating the quality and reliability of shared teaching materials.

The working group is still in the early stages of this effort and has chosen to first focus on small, manageable tasks such as the preparation of static figures or spreadsheets. An initial review of available resources from TC103 members indicated that most existing materials were tailored for advanced courses, with students having a relatively strong background on numerical methods or in the process of developing their numerical skills. These instructors want to keep it for this purpose, although they are available to adapt it for basic soil mechanics courses. Consequently, this project has evolved to focus on creating versatile materials suitable for both basic and advanced courses, i.e. to teach *with* numerical methods and to teach numerical methods.

By providing ready-to-use, high-quality materials, this initiative aims to ease the burden on instructors who face time and resource constraints, while also ensuring that the materials are fully reviewed and ready for broad use. This paper explores the challenges and opportunities of developing such materials and discusses how they can be leveraged to enhance geotechnical engineering education at all levels.

2 Methodology

The work is organized in 4 phases carried out in synergy by the task force of members of TC306 and TC103 as show in **Figure 22**.

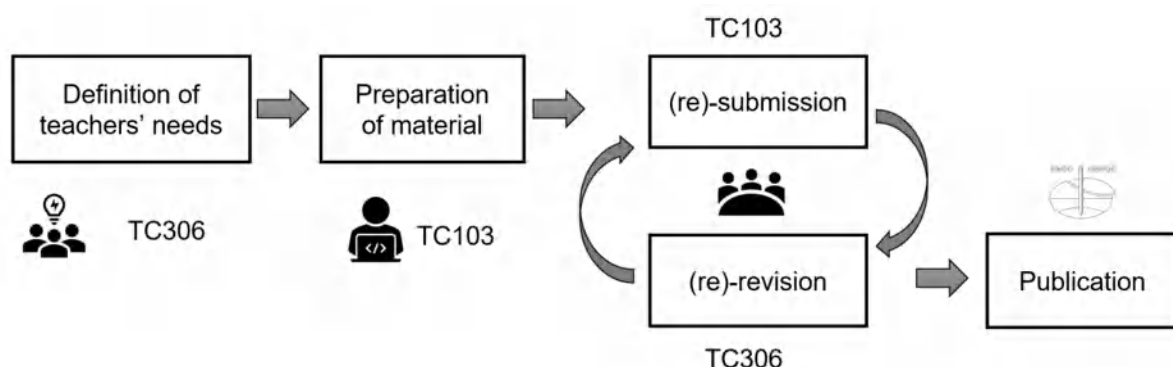


Figure 22. Work flow of the joint TC103-306 collaboration

The first phase of this work involved defining the teachers' needs. This was initially done within the members of TC306, which produced a list of very specific requirements. The teachers' needs should be specific, because generic requirements may generate uncertainty in the work and result in unsatisfactory material. Instead, they must be expressed in a detailed manner, with clear indications of the pedagogical objectives. Most of these needs can be addressed with numerical methods, but in this paper, only a pilot case, specifically the visualization of stresses under loaded areas, is discussed in detail. For the

considered pilot case, the teacher's need is "Stress distributions underneath loaded areas – convince my students and myself that the theory of elasticity performs well: I would like to see how the results would differ if the stress distribution was calculated with something more suitable for soil than the theory of elasticity. I want to see with my own eyes and show students that the difference is indeed small. Also, I would like to provide examples of when the differences are not negligible."

The second phase consists in preparing the educational material. For the pilot case, the analytical solution of the Boussinesq theory is implemented in MATLAB to draw colour figures to better visualize the stress bulbs compared to black-and-white textbook figures. This is an analytical solution based on the assumption of a homogeneous elastic half-space. Equations and charts for several types of flexible surface loads based on the above assumptions are available in many geotechnical textbooks. The set of figures prepared for this pilot case focuses on the load increment generated by a strip load. A strip load is the load transmitted by a structure of finite width and infinite length on a soil surface.

The analytical solution for this case provides the following equations for vertical stress, horizontal stress and shear stress at a point in the homogeneous elastic half-space, with coordinates (x,z):

$$\Delta\sigma_z = \frac{q}{\pi} [\alpha + \sin \alpha \cos(\alpha + 2\beta)] \quad (1)$$

$$\Delta\sigma_x = \frac{q}{\pi} [\alpha - \sin \alpha \cos(\alpha + 2\beta)] \quad (2)$$

$$\Delta\tau_{zx} = \frac{q}{\pi} [\sin \alpha \cos(\alpha + 2\beta)] \quad (3)$$

q is the applied load per unit of area and the geometric quantities and sign convention are defined in Figure 23.

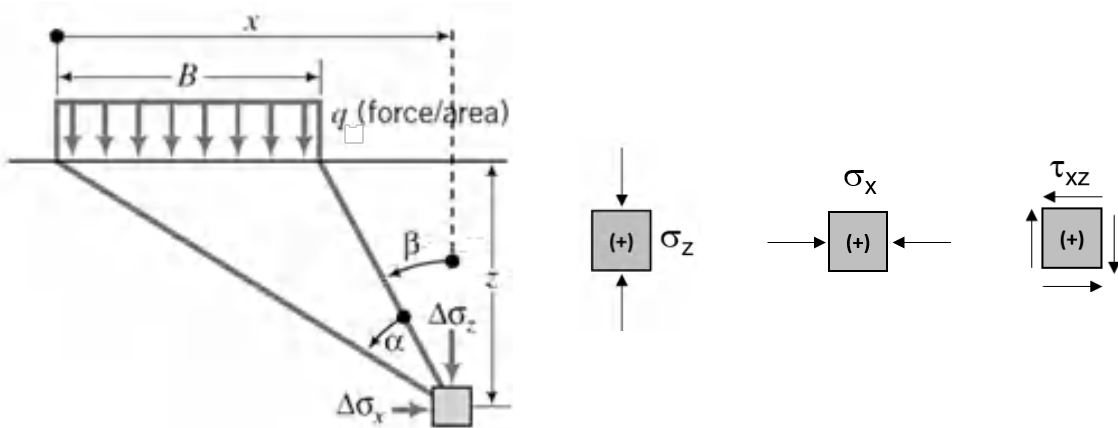


Figure 23. Definitions for the calculation of stress increments due to a strip load at a point in the homogeneous elastic half-space with coordinates (x, z), a and b are positive counterclockwise

These equations are implemented in Matlab to prepare three contour figures of normalized stress increments ($\Delta\sigma_z/q$, $\Delta\sigma_x/q$, $\Delta\tau_{zx}/q$) with normalized coordinates (X/B , Z/B) with origin in the centre of the loaded area. Results are also exported in a normalized format to Excel, which instructors can use to produce additional figures for their classes or provide assignments to students.

The same problem is then solved with the Finite Element Method (FEM). To produce high-quality figures, the software must be flexible enough to adapt the rendering of the results, and many commercial software packages lack this flexibility, thus choosing the right tool is important and could be time-consuming. For this study, GeoStudio 2024 is used. The 2D plane strain problem is simulated considering 6 different models where geometry, material constitutive model and material parameters are varied as follows (Table 5):

- Model 1 serves as a benchmark for analytical comparison, featuring a 100 kPa load on a 1 m-wide strip with a linear elastic material and no gravity.
- Models 2 and 3 introduce gravity and a wider 2 m strip load. Both use a linear elastic material, but with different values of Young Modulus (E). Model 2 represents a medium dense sand, while Model 3 simulates soft clay.
- Model 4 incorporates elasto-plastic behaviour using the Mohr-Coulomb failure criterion.

- Models 5 and 6 implement the Modified Cam Clay model with the load applied at the surface or at the bottom of a 0.5m-deep excavation.

The output visualization is adjusted within the software to obtain a figure that can be easily compared with the one produced in MATLAB or data are extracted to produce graphs depending on the purpose of the model. Finally, the figures are attached to a PowerPoint slide, and text or shapes are added to improve the clarity of the presentation.

A word file with metadata is prepared to improve the usability of the material. For the time being, this word file contains the following information:

A brief title and a descriptive figure title,
 Soil mechanics issue/concept,
 Course chapter/topic,
 Material type,
 Brief articulation of figures' main idea,
 Name and contact of the author,
 Additional material (including detailed explanation of figures and suggestions for instructors),
 License of use.

However, the structure of this document is still under discussion and will be improved in the future.

The third phase is the review phase, in which members of TC306 submitted their recommendations to improve the educational material. Finally, the educational material is revised and resubmitted until a final version is obtained. Note that this process is commonly used for research papers, but it is rarely applied for educational material that are produced in the context of a research project.

The last phase is the publication for the educational material on the ISSMGE website (<https://www.issmge.org/education/peer-reviewed-educational-materials>).

Table 5. Features of the numerical models implemented

Feature	Model 1 (Analytical Comparison)	Model 2 (Elastic - Medium Dense Sand)	Model 3 (Elastic - Soft Clay)	Model 4 (Mohr-Coulomb - Medium Dense Sand)	Model 5 (Modified Cam Clay)	Model 6 (Modified Cam Clay - Excavation)
Load Entity	100 kPa	100 kPa	100 kPa	100 kPa	100 kPa	100 kPa
Load Width	1 m	2 m	2 m	2 m	2 m	2 m (applied at excavation bottom)
Material Model	Linear Elastic	Linear Elastic	Linear Elastic	Elastic-Perfectly Plastic (Mohr-Coulomb)	Modified Cam Clay	Modified Cam Clay
Material parameters	E=30000 kPa, $\nu=0.3$	E=30000 kPa, $\nu=0.3$	E=1000 kPa, $\nu=0.3$	E=30000 kPa, $\nu=0.3$, $\phi=35^\circ$	Table 6	Table 6
Soil Unit Weight	0	20 kN/m ³	20 kN/m ³	20 kN/m ³	20 kN/m ³	20 kN/m ³
Notes	No gravity, used for comparison with analytical solution	Simulates medium dense sand	Simulates soft clay	Shear failure mechanism included in the model	This model has convergence issues	Load applied at excavation bottom

Table 6. Material parameters and initial state parameters of Modified Cam Clay model. *the slope of the critical state line in the p'-q plane can be calculated as $M = 6 \frac{\sin(\varphi)}{3 - \sin(\varphi)} = 1.11$

Parameter		Value
Initial void ratio [-]	e_0	1.0
Overconsolidatio Ratio [-]	OCR	2.0
Poisson ratio [-]	ν	0.3
Slope of critical state line [-]	λ	0.32
Slope of loading reloading line [-]	κ	0.07
Unit weigth [kN/m ³]	γ	20
Friction angle [°]*	φ	28

3 Results of the pilot case

The process presented in the previous section generated the following material, which can be downloaded (<https://researchdata.cab.unipd.it/id/eprint/1549>) as supplementary material of this paper:

- Contour figures of normalized stress increments ($\Delta\sigma_z/q$, $\Delta\sigma_x/q$, $\Delta\tau_{zx}/q$) with normalized coordinates (X/B, Z/B) with origin in the centre of the loaded area calculated analytically. These are in .fig and .jpg format. Files in .fig can only be opened in MatLab by teachers familiar with this program and offer the opportunity to modify or interact with the figures.
- Excel sheets with normalized stress increments ($\Delta\sigma_z/q$, $\Delta\sigma_x/q$, $\Delta\tau_{zx}/q$) with normalized coordinates (X/B, Z/B). Teachers can use it to create additional figures for their classes or provide assignments to students.
- Contour figures of vertical stresses and displacement obtained with FEM using different material parameters and constitutive models.
- PowerPoint slides with the analytical and numerical solutions. These slides can be opened in PowerPoint and modified by the teacher or used as is in their classes.
- A Word file with metadata and instructions for users.
- GeoStudio models. Teachers familiar with the program can inspect and modify them or use to give assignments to students.

This material offers multiple teaching possibilities in both base and advanced courses. In basic courses, teachers can show colour figures of stress under loaded areas instead of classic black-and-white pressure bulbs (**Figure 24**). Distribution of horizontal, shear, mean and deviatoric stresses are also provided, which are rarely shown in textbooks, to offer a more comprehensive understanding of the problem. The Excel file with normalized stress increments can be used to ask students to plot stress variation with distance in vertical or horizontal direction and explore the effect of the size of the loaded area and load magnitude. Students may be asked to implement a similar spreadsheet or a code as an exercise, most undergraduate students certainly have the knowledge to do so.

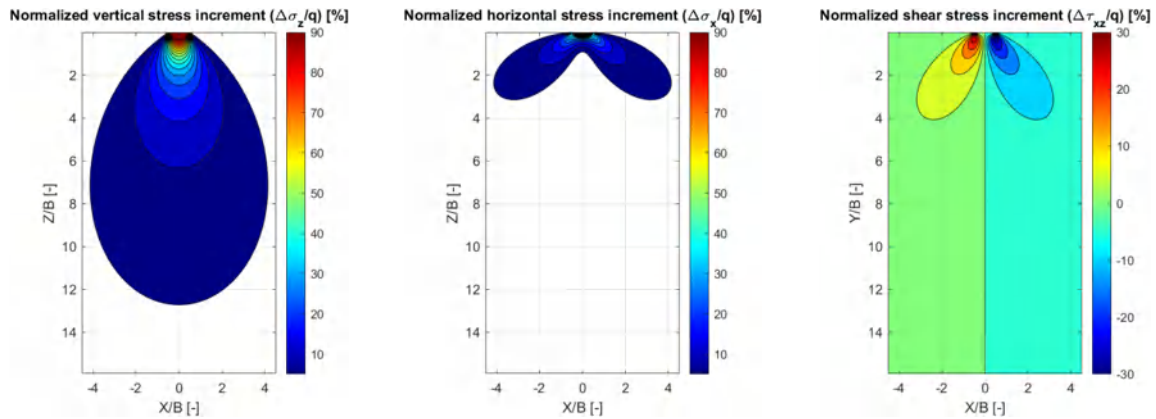


Figure 24. Contour of the analytical solution to calculate normalized stress increments ($\Delta\sigma_z/q$, $\Delta\sigma_x/q$, $\Delta\tau_{xz}/q$) with normalized coordinates (X/B , Z/B) (Model 1 in Table 1). Note that coordinate X is translated with respect to coordinate x used in Equations 1-3 and Figure 2

In order to present the comparison between the analytical solution and the finite element solution, students should be familiar with FEM. In many bachelor courses, students become familiar with FEM before or during the same period of the soil mechanics course, thus the teacher can exploit this knowledge to further discuss the similarities and differences between the two approaches. The author of this paper suggests to avoid the presentation of FEM figures to students that do not have any basic knowledge of the method or to do it with care in order to avoid that this method is perceived as superior, more realistic and always preferable to analytic solutions. Indeed, the quality of FEM results depends on the ability of the engineer to define correctly the model, i.e., geometry, boundary conditions, material parameters, calculation parameters. As an example, for the considered case, if the model boundaries are too close to the loaded area, the results are not in agreement with the analytical solution (Figure 25). It is good to encourage students to compare results of FEM with analytical solutions, discuss differences and similarities, advantages and limitations.

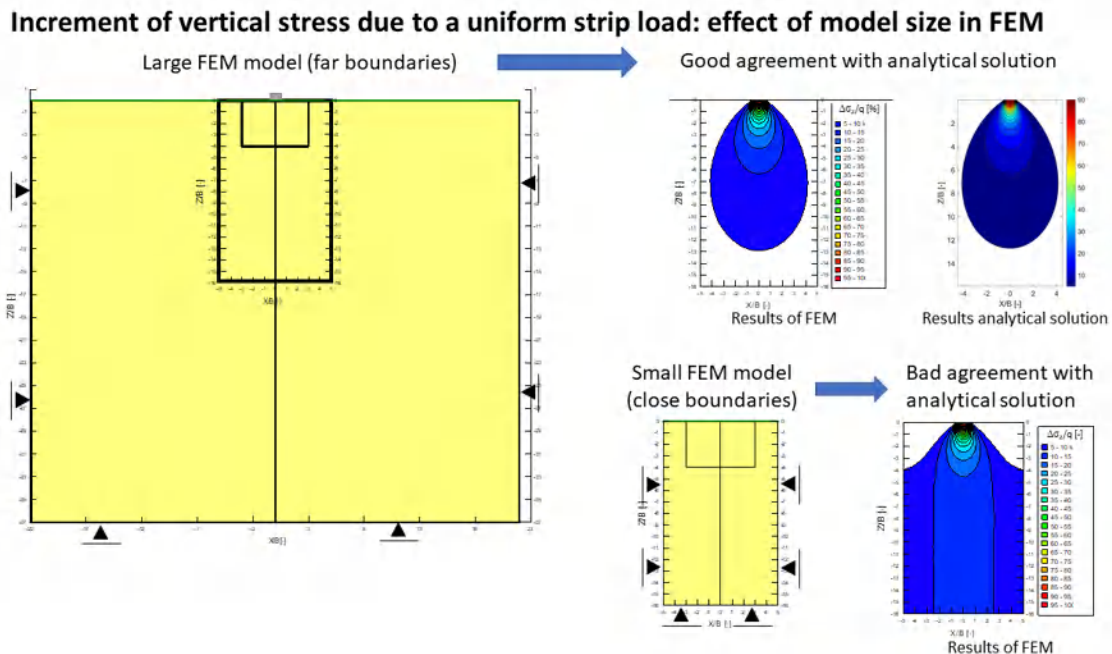


Figure 25. Effect of distance of model boundaries on FEM results (Model 1 in Table 1). High quality figure can be downloaded from <https://researchdata.cab.unipd.it/id/eprint/1549>

While the analytical solution is developed under the hypothesis of homogenous, isotropic, linear elastic half-space, FEM can be used to explore many different conditions such as stratified soil, the effect of soil constitutive model, material parameters, type of load (e.g. non uniform, inclined, applied on rigid or

semi-rigid foundation). Teachers of advanced courses can certainly assign this task to their students. This pilot case explores the effect of Young modulus and constitutive model, in particular the use of an elastic-perfectly plastic (EP) model with Mohr-Coulomb failure criterion and the Modified Cam Clay model (MCC).

The results that illustrate the effect of Young modulus are presented in terms of vertical stress increment and vertical displacement with depth below the centreline and surface displacement (Figure 5). Students should grasp that even if the stress increment is identical, the displacements are proportional to soil compressibility and this relationship is linear because of the assumption of linear elasticity. These results may seem obvious and trivial to students; thus, the teacher should encourage a discussion in the room before showing the results, with special attention to practical implications.

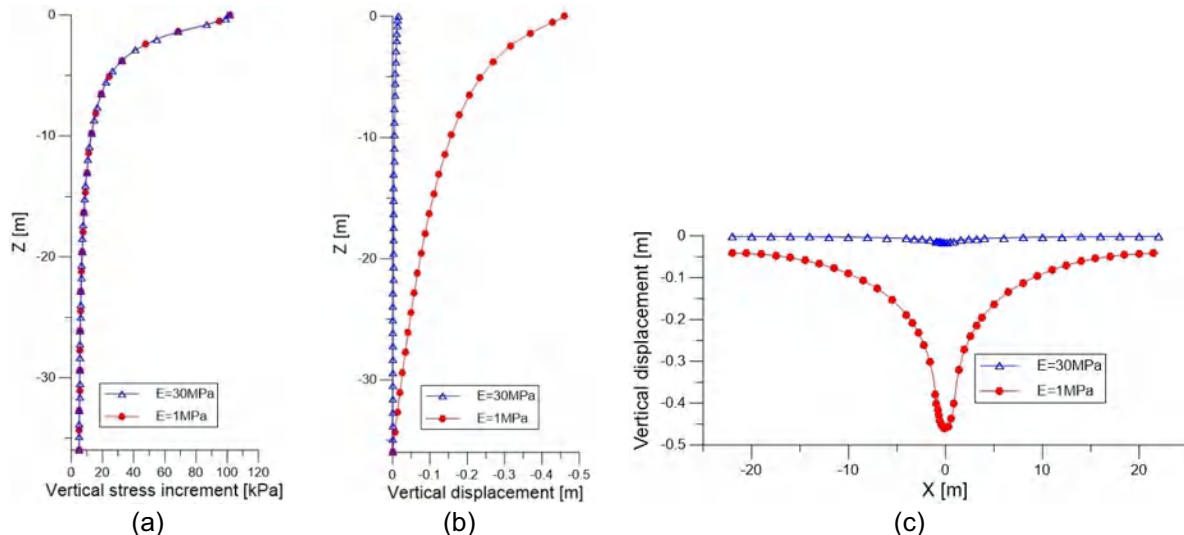


Figure 26. Effect of Young modulus on (a) vertical stress increment at the centerline, (b) vertical displacement at the centerline, (c) vertical displacement at the surface (Model 2 and Model 3 in Table 1)

Elastic perfectly plastic models with Mohr-Coulomb failure criterion are often adopted to simulate the behaviour of coarse grained soils and they may be perceived as an enhancement of linear elasticity. However, in calculating the settlements of shallow foundations, since the load applied for settlement calculation is typically much smaller than the ultimate bearing capacity of the foundation (we often use safety factors between 2 and 3), the soil behaviour is still elastic and the displacements obtained with the two models are identical. This fundamental understanding of soil behaviour and the difference between serviceability limit state (SLS) and ultimate limit state (ULS) is an important aspect that student should learn. To convince students, the teacher can show the vertical displacements calculated with FEM for linear elastic (Model 2 of Table 1) and elastic-perfectly plastic model (Model 4 of Table 1). At this point, the teacher should ask if this constitutive model is realistic and what are the limitations of the assumptions. The discussion in class is certainly useful both in basic and advanced course, although the level of complexity should be adapted to the background of the students.

Soil behaviour, especially in soft clays, is not linear elastic, thus a model including non-linear compressibility should be used. A possibility is the use of Modified Cam Clay (MCC) (Model 5 in Table 1), which is often included in many soil mechanics courses. The replacement of the MCC model in the previous FEM model leads to non-convergence of the results because at low confining stress the stiffness is too small. The teacher can discuss with students what could be the possible solutions, for example: consider an excavation, consider the presence of a dry crust of stiffer soil at the surface. In this pilot case, the excavation is implemented (Model 6 in Table 1). Now the model converges, and the results can be compared with the ones obtained with the Linear Elastic model and Young modulus 1000 kPa (Figure 27). Students should realize that, even if the distribution of vertical stresses is similar in the two cases, due to non-linear soil compressibility, the maximum displacement is higher with the MCC model, but the extent of displacement is much more limited, i.e. with the MCC model the vertical displacements are concentrated closer to the foundation (Figure 28). A discussion on the practical implications of these observations is encouraged.

In basic courses these results can be instrumental to improve the fundamental understanding of soil behaviour under loaded areas and the consequences for practical applications. In advanced courses, these slides may serve as examples, and then students may be encouraged to implement their own FEM codes or to use a commercial software to analyse the same problem and then compare the results with the analytical solution. Several variations can be assigned in terms of geometries, boundary conditions and constitutive models.

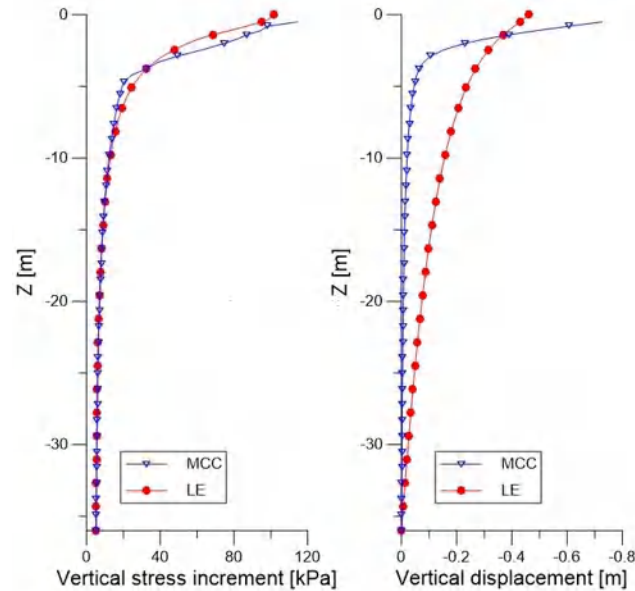


Figure 27. Comparison between linear elasticity (Model 3 in Table 1) and Modified Cam Clay (Model 6 in Table 1): Vertical stress increment and vertical displacement with depth at the centerline

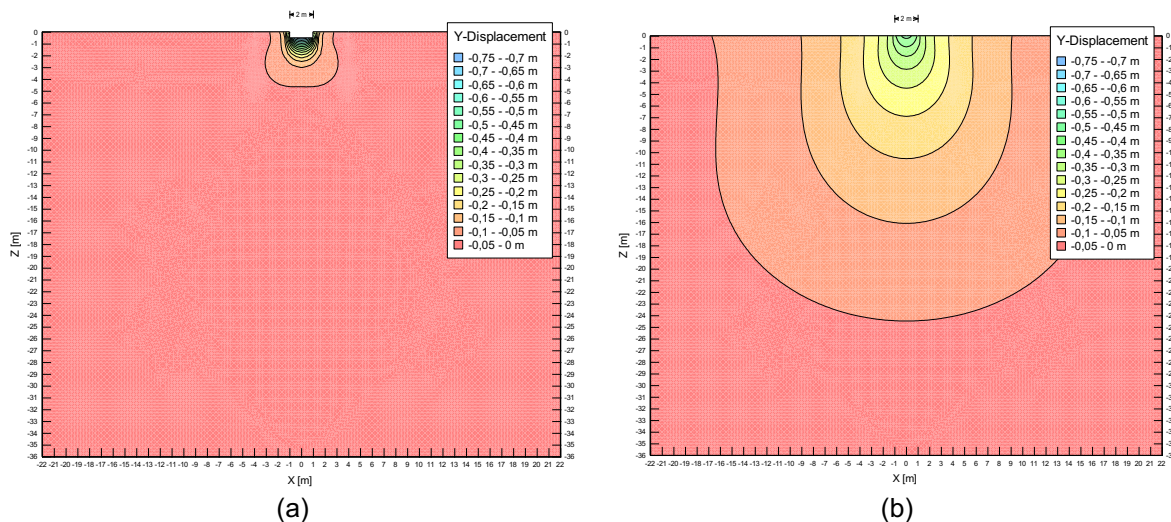


Figure 28. Vertical displacement contour for soft clay modelled with (a) Modified Cam Clay (Model 6 in Table 1), and (b) linear elasticity (Model 3 in Table 1)

4 Concluding remarks

This paper presents a collaborative initiative between TC306 (Geoengineering Education) and TC103 (Numerical Methods) of ISSMGE to develop high-quality, peer-reviewed educational materials using numerical methods. The pilot case discussed in this paper demonstrates how numerical methods can be used to create effective figures, spreadsheets, and presentations to illustrate fundamental concepts in soil mechanics, such as stress distributions under loaded areas.

While numerical methods can be powerful tools to visualize and better understand complex phenomena, it is crucial for teachers to avoid giving students the impression that numerical models are inherently superior to other solutions. Every model has its limitations, and as models become more advanced, the complexity of input parameters and modelling assumptions increases. Modelers should exercise caution and critically evaluate the appropriateness and limitations of the chosen model for the specific problem at hand.

It is important to note that while numerical methods can provide valuable insights and visualizations, they should be used judiciously and in conjunction with analytical solutions and theoretical foundations. The goal should be to leverage numerical methods as complementary tools to enhance students' understanding of fundamental concepts, rather than presenting them as replacements for established theories and methods.

Preparing high-quality educational materials requires a significant effort, involving coding, model setup, post-processing, and documentation. As an example, for the author of this paper, implementing the MATLAB code required approximately 1.5 hours, implementing and calculating all the FEM models took less than 2 hours, and preparing the output visualization, figures, charts and slides required more than 10 hours, writing the documentation required about 5 hours. This amount of time for a single topic is rarely available to a teacher. However, undertaking this task as a community can help mitigate the solitude often experienced in teaching and improve students' learning. By fostering collaboration and peer-review processes within the geotechnical engineering education community, the burden of material development can be shared, and the quality of the resulting resources can be enhanced.

References

Pantazidou, M., Calvello, M. (2023). What kinds of educational material are useful for and desired by university instructors? The case of Geotechnical Engineering. *Soils and Rocks*, 47(2), e2024003623. <https://doi.org/10.28927/sr.2024.003623>

Author's bio

Francesca Ceccato, University of Padua (Italy)

Francesca Ceccato is associate professor at the University of Padua (Italy), where she currently teaches "Geological and Geotechnical Engineering" and "Numerical Modelling in Geomechanics" in the master programs of Water and Geological Risk Engineering and Civil Engineering. She has also been involved in the international teaching program Engineering for Africa within the cooperation between the University of Padua (Italy) and the Ecole National des Travaux Publics (Camerun). She is the secretary of TC103-Numerical methods of ISSMGE, and member of TC-306-Geoengineering education. Her main research topics include numerical modelling in geomechanics, with particular interest in the Material Point Method (MPM), assessment of river embankment vulnerability, soil characterization and the preservation of historical heritage, in particular the study of ancient foundations of the city of Venice. She is member of the core developer team of the open-source code Anura3D, based on MPM, and participates intensively in the activities of the Anura3D MPM research community.

What role should software play in geotechnical education?

N. Utter

Soletanche Bachy, RUEIL-MALMAISON, France
nicolas.utter@soletanche-bachy.com

ABSTRACT: Numerical modeling software available today offer a host of possibilities in terms of both data processing and digital and graphic output. Today's generations of students, immersed in a digital environment since childhood or adolescence, are naturally fond of them. It is tempting, particularly for young geotechnical engineers, to expect a great deal from these tools, even in some cases a complete understanding of a phenomenon they have encountered on a site. Unfortunately, experience shows that this is not the case for junior engineers. It is often deplorable to see an engineer building a sophisticated numerical model straight away, forgetting to think things through beforehand, even though this is essential if the problem is to be solved properly. In light of dual experience as a practitioner in a design office and as a teacher of soil mechanics and geotechnics, we will be looking at how to use digital tools in the context of learning and professional practice. We will address the question of the right place they should occupy in the geotechnical engineer's training curriculum. We will describe the good 'reflexes' that every practitioner should have. This reflection will be extended to the notions of orders of magnitude and the art of engineering, without which the engineer is no more than a calculator that could easily be replaced by an operator simply entering data.

Keywords: Software, Skills, Critical analysis

5 Introduction

As part of their initial geotechnical engineering training, students are exposed to modeling tools during their studies. After learning about theoretical concepts, they are quickly encouraged to put them into practice. Software is extremely user-friendly, so students can apply the theory they have just learned with ease, obtaining results and high-quality graphic representations in just a few hours. We will be looking at the added value of using calculation software in an engineer's training, and the real skills they will need when they start their professional career.

6 Some real-life stories

Examples of real-life situations the author encountered either as an engineer or as a teacher dealing with student engineers will be presented. These situations allow us to understand what difficulties can be encountered in the use of calculation software.

6.1 Boundary conditions

6.1.1 Presentation

A contractor responds to a call for tenders. The excavation is to be carried out with a diaphragm wall and anchors in the sand. The contractor proposed a diaphragm wall one meter thick, held in place by two rows of anchors (Figure 1). The client's consulting engineer questioned this solution, arguing that an 80 cm thick wall with a single support level was sufficient. The company's design office checks its

calculations; it finds no errors and asks the client's consultant for explanations. He details his approach: he has built a finite element model (FEM) and explains that the pumping that will take place within the excavation will cause the water table outside the enclosure to be lowered by 5 meters. Under these conditions, his solution is obviously suitable. This consultant, however experienced and renowned, had simply forgotten in his model the potential imposed by the Nile, some one hundred meters away (Figure 2). So as not to draw attention to the consultant's error, and to win the contract, the contractor replied that the same calculation as his led to the same result, but we invoked the anisotropy of the permeability of the sands to cast doubt on the drawdown and maintain the solution.

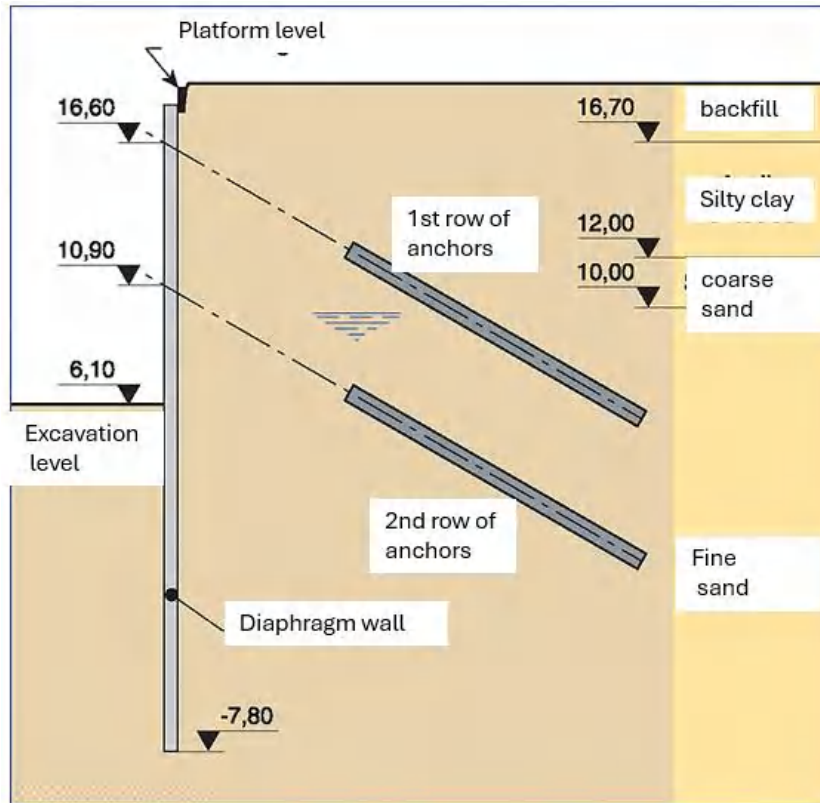


Figure 1. Typical cross section



Figure 2. Excavation completed

The company won the contract. In reality, of course, no drawdown of the Nile occurred. Implementing the customer's solution would inevitably have led to the collapse of the structure. In this case, the FEM calculation was not only totally useless, but harmful and dangerous because it was false, whereas a subgrade reaction model would have been perfectly suitable. Unfortunately, this is not an isolated example, as I recently saw the same error on another site: false boundary conditions in a finite element calculation showed that the excavation of an underground car park would cause a drawdown of 3 meters of the Pacific Ocean.

2.1.2 Lessons

The course naturally covers the hydraulic characterization of soils, the Laplace equation, and general principles of soil flow; emphasis must then be placed on boundary conditions and the physical meaning of the results. The correct way to approach this problem is to first have the students draw a flow network by hand. It is obvious that by drawing such a network, the engineering student would have imposed the correct potential. If we then have them create a FEM model, and they do not impose the correct potential outside the watertight enclosure, they can begin a fruitful reflection.

6.2 General equilibrium

2.2.1 Presentation

This is an excavation carried out using strutted diaphragm wall. The excavation is rectangular, except for a square overhang. During the earthworks, instrumentation revealed that the deformations in the diaphragm wall were significantly greater than those predicted for this particular corner, necessitating the reinforcement of the buttress. Elsewhere, the deformations were of the same order of magnitude as those predicted by the model. Faced with this discrepancy between forecasts and reality, the engineer decided to build a 3D finite element model that took the phasing into account. This took several days of calculations, at the end of which he realized that there were indeed more displacements than predicted in the problem area. If this engineer had drawn up a simple force balance diagram at the design stage, he would have realized that his bracing system was poorly designed: the resultant thrust of the corner was not balanced (Figure 3). This very simple and rapid reasoning, which does not require any software, would have avoided any problems, as well as the resulting increase in costs and delays on site.

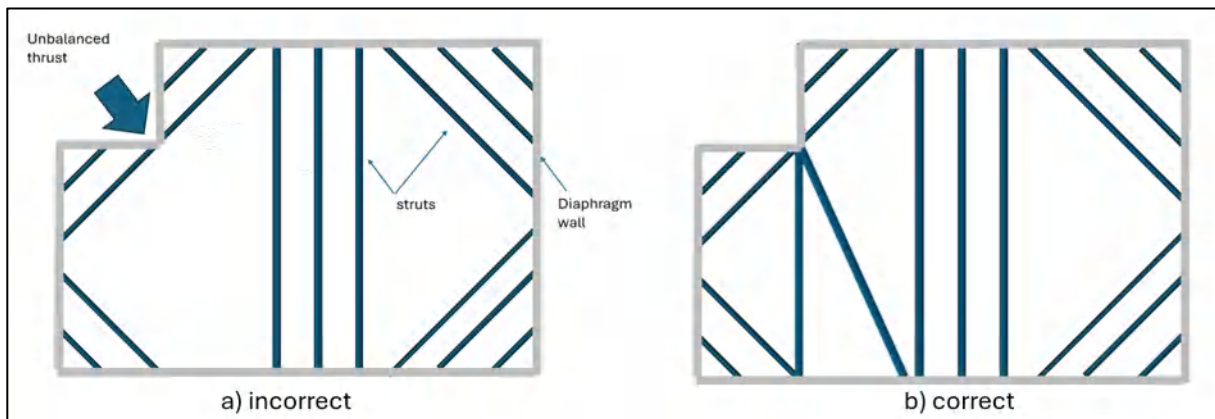


Figure 3. Strutting design

It should be emphasized that the engineer merely noted the results of the FEM calculation, without really looking for the cause of this unexpected behavior of the diaphragm wall. The only skills the engineer needs here are knowledge of the fundamental principle of statics and the ability to draw a force funicular. Besides, it should be noted that, if the thrust had not really been balanced, the diaphragm wall would have collapsed. This did not happen, because the retaining wall, calculated as a juxtaposition of vertical beams, probably decided otherwise: forces had to pass through the capping beam and the joints between diaphragm wall panels, which therefore undoubtedly acted as a screen with greater inertia and this led to much higher than anticipated deformations, stresses on the materials and cracking. It is also

probable that arching vaults were mobilized in the ground, which led to lower thrusts than those estimated; this helped to prevent the retaining system from collapsing.

2.2.2 Lessons

Here we have a "classic" problem of a retaining wall. The student will learn the concepts of thrust, abutment, and balance of the wall. It is fundamental that he also learns that beyond the balance of the screen itself, we must ensure - without software - that all the forces present are well balanced. We are of course leaving the field of "pure" geotechnics, but these notions of general mechanics are essential.

6.3 The supreme judge

2.3.1 Presentation

The project involved the construction of an underground metro station. In this type of project, control of the soil-structure interaction is of course essential. Incorrect assumptions can lead to erroneous load distributions or even load intensities; certain support reactions will be underestimated and others overestimated, and the structure may be needlessly overloaded or on the contrary, disorders (deformations or excessive cracking) or even accidents will occur.

The project manager, the technical controller and the design office of the company carrying out the work discussed the transfer of loads via a column and slabs to the foundations. Especially, questions were raised about the support conditions at the head of the pile. In order to resolve the situation, the project manager asked the company to build a 3-D finite element model, which 'would be the supreme judge'. Of course, the company vigorously refused, arguing that the truth could not emerge from any model. Using reasonable assumptions, based on the method of execution and nature of the connections of the various elements (foundation pile, raft, columns), the calculations were carried out, the work executed, and the structure is performing very satisfactorily.

2.3.2 Lessons

Students have generally learned well a how foundation balances the loads applied to it. This must be supplemented by concepts, even simple ones, of soil-structure interaction, which allow the student to be made aware of the importance of the relative rigidities of the elements. This can be explained to them using very simple models. For example, they can be asked to study a beam on three supports whose rigidity is varied.

6.4 Flow rate through a grouted base

2.4.1 Presentation

To control groundwater for deep excavation, a grouted base was chosen (Figure 4). In order to estimate the flow rate, the company's design office carried out a simple vertical flow calculation through the grouted soil using Darcy's law. The technical controller demanded an FEM calculation. The company replied that it was useless: the injected soil being much less permeable than the natural soil, almost all the pressure losses would be concentrated in the grouted base. To satisfy this requirement, however, it was necessary to carry out the requested numerical calculation, which turned out, as expected, to be completely useless. The flow rate was within a few percent of the same as the one calculated by hand.

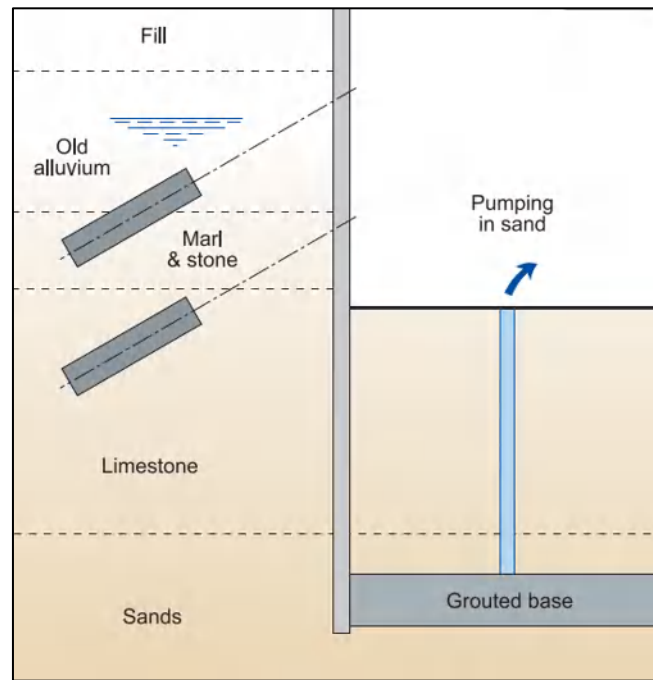


Figure 4. Grouted base

2.4.2 Lessons

The students learned how to calculate vertical permeability in a stratified soil. It is essential to complete this learning by highlighting, on an elementary model with two layers of soil for example, that almost all of the pressure losses are concentrated in the least permeable layer.

6.5 Is Boussinesq old fashioned?

When initial training courses tackle the problem of estimating the settlements induced by a load on a mass of soil, it is natural and logical to start with the theory of elasticity; we then tackle the question of the rigidity of footings, before studying more complex laws of behavior. Most teachers probably proceed in this way.

Of course, to illustrate the method in an elastic environment, students are asked to perform a few elementary calculations, either using analytical formulae by Boussinesq or using abacuses. Whether they have seen finite element calculations on the internet or during a training period in a design office, they are convinced that this method, which is over 150 years old, has no place. Some even think that it is taught because it is very useful to propose exercises. As for abacuses, they are considered prehistoric. It is then easy to show doubtful students that this method is still relevant (Cuiru et al., 2022) and that the art of engineering requires other skills to which we will return.

6.6 Synthesis

The above examples have in common that, in each case : the software was used 'correctly': the engineer has correctly supplied the data to the software, run the calculation and obtained the results.

The problem arose because:

- Not enough thought was given to the design of the structure (e.g. incorrect strutting)
- The data were not correctly defined (e.g. boundary conditions)
- The results were not analyzed correctly (e.g. excessive drawdown)
- The software is expected to do the analysis, replacing the engineer's thought process (e.g. the supreme judge)

Besides, the engineers involved failed to use their knowledge to understand the problem through simple reasoning.

7 What should be taught to geotechnical students?

7.1 The essential skills of the geotechnical engineer

An engineer must respond to a given problem within a given timeframe. To do this, the engineer has to make a number of simplifying assumptions, without which they cannot find a solution, unless they devote energy and time that are incompatible with the world of engineering (Golder 1948). These assumptions must be reasonable: if they are too pessimistic, they lead to excessive consumption of materials and put a strain on projects. If they are too optimistic, they can lead to disruption or damage. This is a particularly complex task for geotechnical engineers, who have to deal with a material they did not create: soil. To achieve this, engineers need to draw on a whole range of essential skills, especially when using calculation software (what follows is, of course, not exhaustive).

A very solid and comprehensive theoretical and technical base is needed. These fundamental and essential skills are acquired by students at engineering schools and universities. A permanent dialogue with the industry is necessary to ensure that the courses are consistent with the needs of industry.

It is essential to know how to reduce any problem to elementary cases. The geotechnical engineer must have in mind simple elementary cases, of which he knows the analytical solution. This will allow him to quickly check that the digital model he designs works well. Even before questioning the relevance of the model, make sure that we understand how the software works.

Here are three examples concerning underground hydraulics.

- Any problem of drawdown under a retaining screen must be able to be reduced, by means of suitable simplifications, to typical flows (CNJOG 2009, see Figure 5): this allows for example the limits of variation of the flow values to be quickly determined. If the numerical model gives other values, the engineer must check his data and his model.
- Let us take the case b) of fig. 5. It is very useful to show students that in simple cases one can have a good estimate of the flow rate by drawing the flow net by hand (Figure 6a) or by using an appropriate abacus (Mandel 1951, Figure 6b), both methods giving similar results as FEM calculation (Figure 6c). This allows, among other things, to make them aware of the essential problem of boundary conditions.
- It is very useful, and quick, to artificially increase the permeability contrast between layers: by doing this the engineer "knows" (or should know) where the water will preferentially pass and will check how the software reacts.

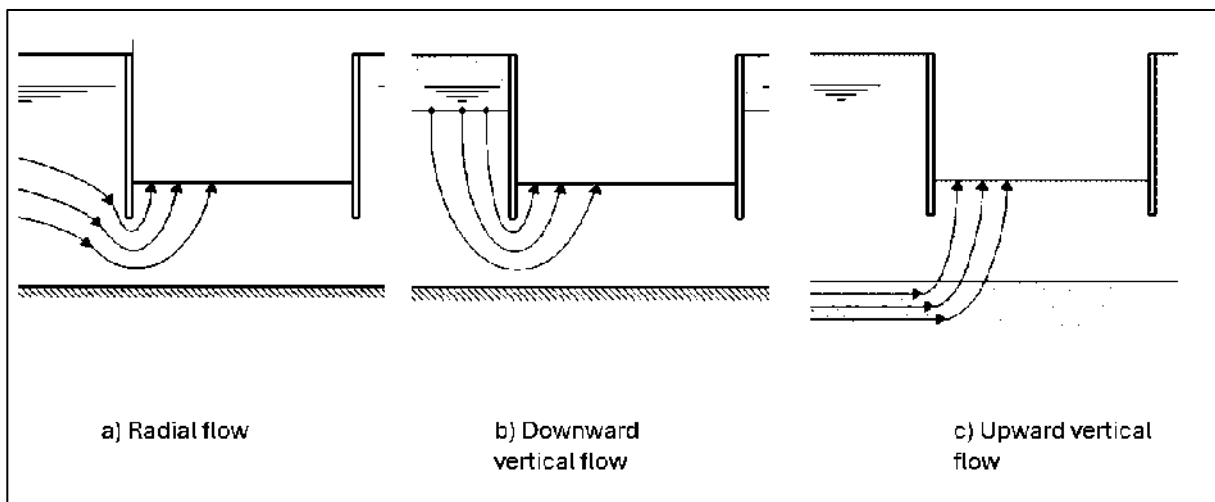


Figure 5. Basic types of flow

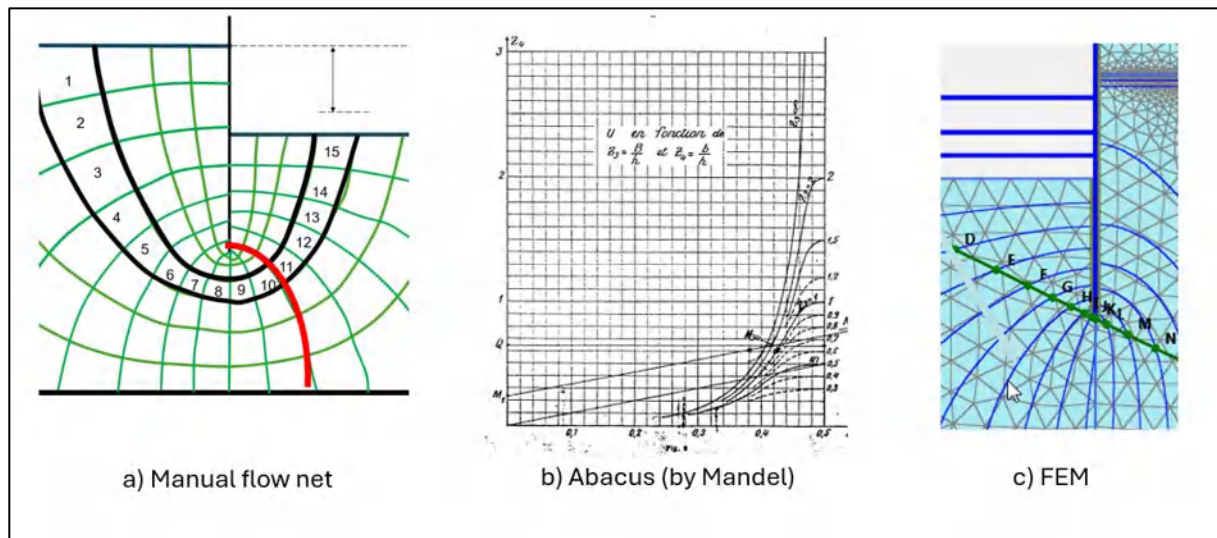


Figure 6. Flow rate estimation

All this should allow engineers to detect the aberrant results, whether they are different from those that one expects, or that shock compared to a similar design made previously. Here we come to the frontier of the possibilities of teaching since knowing how to compare oneself to previous cases requires experience, which one acquires by practicing. And yet, here too, education has an essential role to play:

- education is the place to develop a critical sense (Pecker 2023);
- we can, and we must, accustom students to comparing what they do with previous identical subjects.

7.2 “To see is to know, and to draw is to see well”

This quote (in French: *Voir, c'est savoir, et dessiner, c'est bien voir*) from the architect Eugène Viollet-le-Duc applies fully to the geotechnical engineer.

Students are of course not experienced, but we can give them good habits. When junior engineers join our design office, they are shocked when they are asked to draw to scale, and always to the same scale, the retaining walls that they calculate. They realize after a few months that this simple method allows them to acquire orders of magnitude. If a drawing is very different from what they have already encountered, the question must be asked: either this is explained by a very different condition (nature and resistance of the ground, geometry, etc.) or by an error. This fundamental notion of order of magnitude, of comparison, is essential and naturally finds its place in teaching. This drawing step is obviously essential before starting to build a digital model.

7.3 Software results

Students are always astonished when they are told that the result of software must be known even before the calculation is launched or, to be more precise, that we must understand the behavior of what we are going to model, and the order of magnitude of the results, before building the model. I also gave them the example of professional social networks: we often see an engineer proudly showing a 3D finite element model. The reactions of other followers are enthusiastic: “great job”! It is then necessary to indicate to students that this is not necessary: having built a digital model in no way prejudices its relevance.

7.4 Calculation software and learning

The acquisition of the skills that we have just described will allow us to forge the “art of the engineer”, which goes well beyond calculation and modeling. This learning does not require any software.

Calculation software can be used, in an elementary case, to highlight the sensitivity of parameters, always keeping in mind being able to compare the results with those of an analytical approach; their use can also help to raise students' awareness of the importance of different parameters by varying them

rapidly. The manipulation of the software is within the reach of any engineer. The real added value of learning includes warnings, the precautions that the engineer must respect when using software.

Software can be used to construct new abacuses, very practical tools that should probably be brought up to date. This would have the educational interest of asking students to think about the physical phenomenon, its modeling and the dimensionless parameters necessary to construct the abacuses. Without going as far as constructing abacuses, the software is useful for its speed in performing parametric studies; this is also a method frequently used in design offices.

Finally, in the context of a more advanced specialization in geotechnics, the software is of course useful for exploring more sophisticated behavioral laws, for example.

7.5 The art of engineering

It is all of these skills that are covered by "the art of the engineer": by relying on solid theoretical and technical bases, knowing how to pose reasonable hypotheses, building a model and ensuring its proper functioning while keeping principles and orders of magnitude in mind.

Prof. H. Cambefort (technical director of Soletanche from 1946 to 1975) used to say: *"To solve an underground hydraulic problem, an engineer has a number of formulae at his disposal. How do you choose? If the engineer is good, the formula is good. Otherwise..."* The same goes for numerical models: if the engineer is good, the model is good. Formulae and calculation software are only tools at the service of engineering. The engineering student will have to learn to use simple tools with proven methods and results; he will only have to use more sophisticated tools after careful consideration, if the physics or certain specific aspects of the projects require it.

The last essential phase - which is not the subject of this article - is of course the confrontation of the real behavior of the work with the expected behavior, to validate, or modify the hypotheses envisaged.

7.6 Some tips for students for practicing digital models

We recommend that students apply the following principles.

- Mastery of theoretical concepts is essential.
- A numerical model is not "reality" but a simplification of reality.
- Before starting a numerical model, it is necessary to build the geotechnical model. It is essential to draw it, indicating the loads, boundary conditions, and the characteristics of the elements.
- We must then, using simple methods, estimate the behavior of what we are going to model. Where will the water flow? How will a given element deform? Where will the efforts go? Can they be balanced?
- We must then have an order of magnitude of the expected results, by analytical methods, approximate methods, abacuses, comparison with similar models.
- We can then finally create the digital model and start the calculations.
- It is then necessary to check that the model reacts correctly. What happens if we modify a support of a retaining wall? If we increase the rigidity or resistance of a soil? If we modify the permeability? Etc.
- We will then compare the results with the pre-established orders of magnitude.
- Finally, it is essential to question the physical relevance of the results obtained.

8 Concluding remarks

The examples given show that the errors made did not come from poor handling of calculation software, but from lack of control, errors in reasoning or modeling. In addition to the essential theoretical foundation provided to engineering students, teaching about software should therefore be devoted not to its use, but to methods for verifying the relevance of the hypotheses and the consistency of the results obtained.

Acknowledgements

The author thanks Prof. Claude Hovart and pays tributes to Prof. Jean-Louis Proust (†), his soil mechanics and geotechnics teachers, with whom he later had the privilege of working at Soletanche Bachy.

References

- CNJOG (2009). Norme d'application de l'EC7: écrans de soutènement, pp. 135-136, AFNOR, France.
- Cuira, F., Lopes, A. (2022) Apport d'une caractérisation plus fine des terrains. Cfms; cfms-sols.org/documentation
- Golder, H.Q. (1948). Coulomb and earth pressure. *Géotechnique*, 1, pp. 66-71.
- Mandel, J. (1951). Écoulement de l'eau sous une ligne de palplanches, *Travaux* n°197, pp. 273-281, éditions science & industrie; France.
- Pecker, A. (2023). The eighteenth Mallet-Milne lecture. *Bulletin of Earthquake engineering*, 21, pp. 3087-3132.

Author's bio

Nicolas Utter, Soletanche Bachy (France)

President of the board of the National School of Geology in Nancy (France) since 2024, Nicolas Utter has devoted his entire career to the Soletanche Bachy group, where he is currently director of technical studies. President emeritus of the French Committee for Soil Mechanics and Geotechnical engineering, publishing editor of "Revue française de Géotechnique", he is involved in improving knowledge and disseminating it, teaching and standardization. He led the organization of the scientific seminar "Coulomb 2023: a geotechnical tribute" to mark the 250th anniversary of the publication of the founding memoir of Charles-Augustin Coulomb. Nicolas Utter teaches soil mechanics and geotechnics at the Higher School of Public Works (Cachan, France) since 15 years, and has been involved in higher education in geotechnics for almost twenty years, both in initial training and in continuing education. Member of the French mirror group of EC7, he also chairs the technical commission of the SOFFONS (French union of deep foundations companies).

Geosynthetics in the classroom: Educating future engineers and their instructors

J.G. Zornberg

University of Texas at Austin, Austin, Texas, USA
zornberg@mail.utexas.edu

ABSTRACT: Geosynthetics—synthetic geomaterials—have become essential in geotechnical engineering, yet their coverage in undergraduate civil engineering curricula remains limited. This paper addresses this educational shortfall by proposing a teaching framework that parallels the instruction of geosynthetics with that of soils, promoting a more cohesive understanding of geotechnical materials overall. The approach emphasizes introducing geosynthetics early in the curriculum, especially as part of the introductory geotechnical engineering course. This strategy aligns with the International Geosynthetics Society's global initiative to support faculty in incorporating geosynthetics into their teaching. The paper also presents results from an international faculty survey across nine countries, revealing the typical structure of geotechnical education and the limited inclusion of geosynthetics, which are often confined to electives or brief mentions. Findings show that, although geotechnical engineering is generally a required subject—particularly outside the United States—, instruction on geosynthetics remains uncommon. This gap can be effectively addressed through targeted educational strategies that introduce geosynthetics in a way that reinforces core geotechnical concepts while emphasizing the vital role of geomaterials as construction materials. These insights highlight the importance and feasibility of integrating geosynthetics into the core civil engineering curriculum to better prepare graduates for modern engineering challenges.

Keywords: Undergraduate Education, Geosynthetics, Survey, Curriculum

1 Introduction

Geosynthetics have become essential materials in contemporary geotechnical engineering practice, offering innovative, cost-effective, and sustainable solutions for a broad range of infrastructure challenges. Despite their widespread use, instruction on geosynthetics remains largely absent from undergraduate civil engineering programs. A key reason for this absence is that many current faculty members were not exposed to geosynthetics during their own academic training, given that the field has only matured in recent decades. This generational gap has contributed to the persistent exclusion of geosynthetics from core civil engineering curricula.

Incorporating geosynthetics into undergraduate education may present significant challenges. A key obstacle is the curriculum: Civil engineering programs face growing demands to cover a broader technical knowledge within limited credit hours. Faculty must make tough choices about which topics to include, often favoring traditional subjects over newer ones. Although geosynthetics are now recognized as essential geomaterials used in nearly all areas of geotechnical engineering, they are frequently overlooked in undergraduate instruction.

Another significant obstacle is the lack of faculty preparedness. Since many geotechnical educators were not taught about geosynthetics themselves, they might feel unprepared to introduce this topic in their courses. While continuing education and professional training can address practical applications, it can be argued that instruction on the fundamental behavior of geosynthetics belongs earlier in the learning process, alongside foundational topics such as the mechanical and hydraulic properties of soils.

Integrating geosynthetics into the introductory geotechnical engineering course offers a strategic approach. This can be achieved by framing geosynthetics as part of the broader family of geomaterials,

which includes both natural and synthetic materials used in geotechnical engineering. Notably, geomaterials can be studied not only as existing materials that remain in place to support infrastructure (e.g., foundation soils), but also as construction materials actively used to build the infrastructure itself, such as embankments, dams, or roads. Introducing geosynthetics within this construction-materials framework helps students develop a unified understanding of how different materials contribute to engineering performance, from both a foundational and structural standpoint.

Meaningful exposure to geosynthetics in undergraduate civil engineering programs can be achieved with minimal disruption to the curriculum. Even brief, well-integrated instruction—such as a single lecture—can serve as a starting point. This paper supports that premise by offering a structured framework to help incorporate geosynthetics into core geotechnical education. It begins with a basic overview of geosynthetics, including their classification by type and the engineering functions they perform. This establishes a shared instructional vocabulary and highlights opportunities to integrate geosynthetics alongside traditional geomaterials.

As part of this paper's preparation, an international survey was created and distributed, and its results were analyzed to evaluate the current state of undergraduate geotechnical education in selected countries. The results provide insights into the structure of geotechnical courses, the limited focus on geosynthetics, and regional differences in curriculum emphasis.

The paper also describes the International Geosynthetics Society (IGS)'s “Educate the Educators” (EtE) initiative, which offers faculty instructional resources and training to help incorporate geosynthetics into existing courses (Zornberg et al., 2020; Gardoni et al., 2024).

Additionally, the paper details specific educational strategies that align the teaching of geosynthetics with fundamental geotechnical concepts. These include introducing geosynthetics early as construction materials, emphasizing their parallels with soil behavior, and drawing on their distinct two-dimensional characteristics to reinforce key mechanical and hydraulic principles. Instructors are encouraged to revisit the topic of geosynthetics in subsequent courses as applications are examined, enhancing students' conceptual continuity.

By integrating survey data on the state of geotechnical education, technical content, institutional context, and pedagogical strategies, the paper provides a practical model for incorporating geosynthetics into undergraduate teaching, helping to ensure that future civil engineers are equipped to work with both traditional and emerging construction materials.

2 An Overview of the Basic Content on Geosynthetics

2.1. General Overview

Geosynthetics are synthetic materials used in geotechnical engineering applications to enhance civil infrastructure's performance, durability, and sustainability. Their use has evolved significantly since the 1960s, when geotextiles were first deployed in filtration and separation roles. Over the decades, the family of geosynthetics has expanded to include geogrids, geomembranes, geonets, geocomposites, and geocells, among others. These products are now routinely used in functions such as separation, reinforcement, filtration, drainage, barrier protection, and erosion control. Their versatility and reliability have made them integral components in the construction of roads, retaining structures, landfills, embankments, and environmental protection systems. This section introduces their classification and performance characteristics. The subsequent sections, 2.2 and 2.3, will define the scope of this paper and further categorize geosynthetics by type and function.

2.2. Types of Geosynthetics

The term “geosynthetics” covers a wide range of synthetic materials used in contact with soil, rock, and other geotechnical engineering-related materials. These products are specifically engineered to perform a variety of functions—such as reinforcement, filtration, and barrier protection—in civil, environmental, and transportation projects. Each type of geosynthetic has unique features that make it especially suitable for specific uses. Understanding the differences among these materials is fundamental for their correct design and application. The main categories of geosynthetics, in the order most commonly used in educational settings, include:

- **Geotextiles** are permeable fabrics, typically made from polypropylene or polyester, that improve soil behavior. They are woven (structured) or nonwoven (felt-like).

- **Geogrids** are open-grid structures formed by polymers, used primarily for reinforcement. Their open configuration allows for soil interlock and transfer of tensile loads, making them effective in applications such as base reinforcement and retaining wall stabilization.
- **Geonets** involve intersecting ribs in a planar setup, usually made from extruded polymers. They mainly drain by enabling in-plane flow, commonly used in landfills and subsurface drainage.
- **Geomembranes** are essentially impermeable polymer sheets used as hydraulic barriers in landfill liners, ponds, and canals to prevent fluid migration.
- **Geosynthetic Clay Liners (GCLs)** are factory-made hydraulic barriers with bentonite clay between geotextiles or bonded to a geomembrane, mainly used as alternatives to compacted clay liners in containment systems.
- **Geocells** are three-dimensional, honeycomb-like structures usually made from high-density polyethylene (HDPE). When filled with soil or aggregate, they offer confinement and distribute loads, making them suitable for slope protection and load support.
- **Geofoms** are lightweight EPS blocks that reduce load on soils. Their low density and easy installation make them ideal for embankments over soft soils and slope stabilization.
- **Geocomposites** are hybrid systems that combine two or more types of geosynthetics—such as geotextiles bonded to geonets or geomembranes—to serve multiple functions at the same time, like drainage, filtration, or acting as a barrier and protective layer.

This classification provides a basic understanding for educators and students alike. The following section will cover the main functions these geosynthetic products are designed to perform.

2.3. Functions of Geosynthetics

Geosynthetics serve a wide range of functions in geotechnical, environmental, and transportation engineering applications. These functions describe the essential ways in which geosynthetic materials interact with surrounding soils and other system components to achieve specific performance outcomes. A single geosynthetic product may perform one or multiple functions simultaneously, depending on its properties and the configuration in which it is used. Understanding these different functional roles is crucial for proper design, specification, and instruction.

The primary functions of geosynthetics, as acknowledged in engineering practice and design guidelines, include (Koerner, 2012; Zornberg, 2017):

- **Separation:** The geosynthetic, placed between two dissimilar materials, maintains them apart to keep their integrity and functionality.
- **Filtration:** The geosynthetic allows water (or other liquids) to flow across its plane while retaining upstream fine soil particles.
- **Reinforcement:** The geosynthetic develops tensile forces intended to maintain or improve the stability of the soil-geosynthetic composite
- **Stiffening** (also known as stabilization): The geosynthetic develops tensile forces intended to control the deformations in a soil-geosynthetic composite.
- **Drainage:** The geosynthetic allows liquid (or gas) flow within the plane of its structure.
- **Hydraulic/Gas Barrier:** The geosynthetic minimizes the cross-plane flow, providing containment of liquids or gases
- **Protection:** The geosynthetic provides a cushion above or below other material (e.g., a geomembrane) to minimize damage during construction or operation

These seven functions are not merely classifications; they are essential to define the relevant engineering properties for a geotechnical project. They are also associated with mechanisms by which geosynthetics contribute to the overall performance and longevity of geotechnical systems. For example, a single geosynthetic layer in roadways may simultaneously provide separation, reinforcement, and drainage. Understanding these functions is essential for helping students recognize the multifaceted role of geosynthetics in civil infrastructure.

3. An International Survey on Undergraduate Geotechnical Engineering Education

3.1. Civil Engineering Undergraduate Education in Representative Countries

Civil engineering undergraduate programs worldwide differ in structure, duration, and emphasis, reflecting the diversity of national educational systems. This section provides a comparative overview of

undergraduate civil engineering education in nine countries selected for their representative and contrasting educational models: Argentina, Brazil, Canada, Colombia, Germany, Greece, India, Turkey, and the United States. These countries span multiple continents and higher education frameworks, offering valuable insights into how undergraduate engineering education is organized globally.

Table 1 provides a comparative summary of civil engineering degree requirements across the nine countries. It includes degree duration, type, language of instruction, licensing status, and typical final requirements.

Table 1. Summary of Undergraduate Civil Engineering Education in Selected Countries

COUNTRY	DEGREE TITLE (ENGLISH TRANSLATION)	DURATION	DEGREE TYPE	LANGUA GE	LICENSE REQUIRED?	FINAL PROJECT / INTERNSHIP
ARGENTINA	Civil Engineer	5–6 years	Single-cycle	Spanish	Yes (provincial councils)	Final project, internship
BRAZIL	Civil Engineer	5 years	Single-cycle	Portuguese	Yes (CREA)	TCC (capstone), supervised internship
CANADA	B.Sc. / B.Eng. in Civil Engineering	4 years	Bachelor's	English / French	Yes (provincial boards)	Capstone project, optional co-op
COLOMBIA	Civil Engineer	5 years	Single-cycle	Spanish	Yes (COPNIA)	Final project, internship
GERMANY	B.Sc. + M.Sc. in Civil Engineering	3 + 2 years	Bologna model (3+2)	German	Yes (state engineering chambers)	Thesis, internships common
GREECE	Diploma in Civil Engineering	5 years	Equivalent to an Integrated Master's	Greek	Yes (TEE)	Thesis, design studio
INDIA	B.Tech / B.E. in Civil Engineering	4 years	Bachelor's	English	Optional (state-specific)	Internship often required
TURKEY	B.Sc. in Civil Engineering	4 years (+1 prep)	Bachelor's	Turkish / English	Yes (Chamber of Civil Engineers)	Mandatory internship
UNITED STATES	B.S. in Civil Engineering	4 years	Bachelor's	English	Yes (PE licensure path)	Capstone project, internship encouraged

Despite their differences, civil engineering programs in these countries share a common goal: to prepare students for professional practice through foundational training in engineering sciences, specialized instruction in civil engineering disciplines (e.g., structural, geotechnical, hydraulic, and transportation), and practical experience. However, a major difference lies in the duration of the undergraduate degrees offered. These can be summarized as follows:

Four-year programs are standard in Canada, India, Turkey, and the United States, where students typically earn a Bachelor of Science (B.Sc., B.E., or B.Tech) in Civil Engineering. These programs generally focus on foundational coursework during the first two years, followed by specialization and design-focused courses in the final years. Internships or co-op experiences may be required or highly encouraged.

Five-year programs are standard in Argentina, Brazil, Colombia, and Greece, often structured as single-cycle professional degrees or integrated masters-level diplomas. These programs offer a more comprehensive curriculum, usually including mandatory internships and final thesis projects. In Greece, the five-year Diploma in Civil Engineering is often deemed an integrated master's degree (EQF Level 7). Germany follows the Bologna 3+2 model, where students first earn a 3-year B.Sc., followed by an optional 2-year M.Sc. for full professional qualification. Although technically modular, completing the full five-year cycle is standard for students aiming to become licensed civil engineers. These variations in duration influence how geotechnical and specialized content, including geosynthetics, is incorporated into the curriculum. For example, five-year programs typically provide more time for detailed coverage of advanced topics or design applications, whereas four-year programs may rely on technical electives or graduate studies to achieve similar depth.

3.2. Characteristics of the International Survey

To better understand how geotechnical engineering—and specifically geosynthetics—is taught at the undergraduate level, an international survey was conducted using the Qualtrics XM platform. The survey targeted civil engineering faculty members across nine countries: Argentina, Brazil, Canada, Colombia, Germany, Greece, India, Turkey, and the United States. These countries were chosen to represent a diverse range of educational models and program structures, as outlined in the previous section.

The survey included a total of 339 respondents out of 466 identified civil engineering programs, resulting in an exceptionally high response rate of approximately 73%. Table 2 summarizes the total number of civil engineering programs identified in each country, along with the number of responding institutions and their response rates. Only one faculty member from each identified academic institution was contacted to complete the survey. The questionnaire was structured into several parts, two of which are evaluated in this paper. The first part gathered general information about undergraduate civil engineering programs, focusing on geotechnical engineering education. It addressed the number of required versus elective geotechnical courses, when these courses are offered during the program, and allows providing information on whether they include laboratory or field components. The second part examined the inclusion of geosynthetics in the curriculum—both as required and elective courses—and gathered input on teaching strategies and perceived challenges.

Table 2. Summary of Survey Responses

Country	# Programs Identified	# Responses	Response Rate
Argentina	22	19	86%
Brazil	56	44	79%
Canada	22	19	86%
Colombia	25	14	56%
Germany	59	28	47%
Greece	7	7	100%
India	49	36	73%
Turkey	97	64	66%
USA	129	108	84%

The survey was designed using closed-ended questions to facilitate comparative analysis, with optional open-text fields allowing respondents to provide more details about specific practices or challenges. Participants were also asked to share information about the institutional context, including program size, degree titles, and country-specific licensing or accreditation requirements. The survey was distributed in English and administered electronically, enabling broad geographic participation with minimal logistical obstacles.

3.3. Structure of the Survey Instrument

The international survey that informed this study was developed and conducted using the Qualtrics XM platform. It specifically targeted university faculty members who teach geotechnical courses and aimed to capture both structural and instructional aspects of the curriculum. The survey gathered geotechnical

engineering course data from both undergraduate and graduate levels. However, this paper will focus only on the data related to undergraduate education.

The questionnaire included about twenty questions, organized into thematic sections. The first set gathered basic institutional details, such as the country and name of the respondent's university, the highest degree offered by the institution, and any additional information the respondent might be willing to share. Subsequent questions focused on the structure of geotechnical education within the undergraduate curriculum. Respondents were asked about the number of required and elective geotechnical courses, the academic year when these courses are typically offered, and the extent to which laboratory or field components are included. Particular emphasis was placed on whether soil mechanics or introductory geotechnical engineering is considered a mandatory subject.

The survey then turned to the teaching of geosynthetics, asking questions to determine whether geosynthetics are included in mandatory courses, elective courses, or not offered at all. Respondents were asked to estimate the number of contact hours dedicated to geosynthetics and to describe the instructional context in which the topic is presented—whether as part of a general discussion on construction materials, within design applications, or as a standalone subject. Open-ended prompts allowed faculty to elaborate on specific challenges or to share institutional practices regarding geosynthetics instruction.

Additional optional questions explored faculty views on the importance of teaching geosynthetics at the undergraduate level, their interest in faculty development opportunities, and their use of supplemental teaching resources, such as industry case studies or materials from professional societies. The analysis and findings from the survey data are offered in Section 5 of this paper.

4. The Case for Teaching Geosynthetics: Needs, Challenges, and Opportunities

4.1. The Need to Teach Geosynthetics

Geosynthetics have become essential in modern civil engineering. From stabilizing roadways and reinforcing walls to environmental containment and drainage, these materials are used in a wide range of infrastructure projects and have been included in national and international design standards (e.g., AASHTO, ISO, CEN). This widespread use reflects a key development in the field: What was once considered a specialized material class is now essential to everyday engineering practice. Reflecting this broad institutional integration and practical importance, the global geosynthetics market exceeded USD 16 billion in 2024 and is projected to grow to over USD 27 billion by 2033 (Precedence Research, 2024). These figures highlight an important educational need: geosynthetics are no longer peripheral to geotechnical engineering—they are now a central component of its current and future practice.

Introducing geosynthetics also helps bridge the gap between theoretical learning and real-world design practice. Unlike natural soils, geosynthetics are engineered materials with tightly controlled properties. This makes them ideal for helping students understand material selection, specification, and performance-based design. Furthermore, geosynthetics typically function within composite systems—working alongside soils or other materials—so their study naturally promotes systems thinking. When taught thoughtfully, geosynthetics become an educational link between the mechanics of materials and the complexities of infrastructure design. As Dr. J.P. Giroud, founding father of the IGS and 53rd Terzaghi Lecturer, insightfully remarked (Giroud, 2008): “What started as technology transfer from geotechnical engineering to geosynthetics engineering ended as technology transfer from geosynthetics engineering to geotechnical engineering.” This reversal underscores how geosynthetics have evolved from being an applied extension to becoming a driver of innovation in geotechnical thinking.

There is also a strong case for incorporating geosynthetics from a sustainability perspective (Damians et al., 2018; Zornberg et al., 2024). These materials often allow for thinner pavement layers, more efficient earth structures, and reduced use of natural aggregates—all of which contribute to lower carbon footprints and less environmental impact. At the same time, their use generally enhances durability and extends service life, aligning with the profession’s focus on resilient and sustainable infrastructure. For students, understanding these benefits helps reinforce that good engineering not only considers technical feasibility but also emphasizes long-term performance and environmental responsibility. Furthermore, including these topics in the curriculum supports key learning outcomes promoted by engineering accreditation organizations such as ABET, which requires students to understand the environmental and societal impacts of engineering solutions (ABET, 2022). It also aligns with international sustainability initiatives, especially the United Nations Sustainable Development Goals (UN, 2015), including SDG 9 on Industry, Innovation, and Infrastructure and SDG 11 on Sustainable Cities and Communities (Touze, 2021).

Importantly, this curricular modernization is both feasible and scalable. A meaningful introduction to geosynthetics can be achieved in just one class session within an introductory geotechnical engineering course. Thanks to initiatives like the International Geosynthetics Society’s Educate the Educators (EtE) program, faculty now have access to modular content, instructional materials, and peer support that make integration simple. Once introduced, geosynthetics can then be revisited in more advanced or elective courses, allowing institutions to expand coverage naturally based on program goals and instructional capacity.

4.2. The Challenges of Teaching Geosynthetics

Despite the benefits mentioned earlier, incorporating geosynthetics into undergraduate civil engineering programs presents specific challenges—some related to curriculum design, others to faculty readiness, and still others to the scope and nature of the subject itself. These challenges are not impossible to overcome, but they do require targeted strategies.

One major obstacle is the curriculum limit faced by most civil engineering programs. As the technical knowledge needed by graduates keeps growing, undergraduate programs struggle to cover more material within a set number of credit hours. This forces a tough choice: adding new content often means cutting back on existing topics. In this context, newer materials like geosynthetics—despite their well-established role in engineering—are often left out of the core curriculum.

Another challenge is the limited student population that may benefit from geosynthetics instruction. In many programs, exposure to geosynthetics is limited to elective courses or isolated lectures, which means many students graduate without any formal education on the subject. To integrate geosynthetics

into the core of geotechnical engineering, their inclusion should be expanded to reach all undergraduate students, even if only through a brief but strategically placed module in a required course.

The faculty readiness barrier is also significant. As already mentioned, many professors teaching geotechnical engineering today were not introduced to geosynthetics during their own education. As a result, they may lack confidence and instructional resources to teach the topic effectively. Although initiatives like the IGS's Educate the Educators program are helping to address this issue, gaps in faculty training still pose a significant obstacle to widespread adoption.

Finally, there is the didactic challenge posed by the very nature of geosynthetics. The topic of geosynthetics covers a wide variety of material types, each with different functions, properties, and applications. This complexity can seem intimidating, especially when compared to the more specific behavior of traditional soils. However, this same complexity offers valuable opportunities to connect with core geotechnical principles. When introduced thoughtfully, geosynthetics can help explain concepts like soil-structure interaction, hydraulic conductivity, and reinforcement mechanisms.

These challenges underscore the need for a teaching approach that is both strategic and inclusive. While it might not be possible to dedicate an entire course to geosynthetics in every program, even brief and well-placed exposure can ensure that all future civil engineers graduate with at least a basic understanding of these commonly used construction materials.

4.3. The Appeal of Teaching Geosynthetics

The appeal of teaching geosynthetics extends beyond their technical relevance—it also lies in their ability to inspire thoughtful, creative, and well-rounded engineering professionals. As Zornberg (2012a) points out, ingenuity is a key trait of geotechnical projects involving geosynthetics. These projects often require innovative thinking, adaptable solutions, and interdisciplinary integration. Introducing students to the ingenuity of geotechnical projects involving geosynthetics early in their education can be highly motivating, fostering a sense of discovery and highlighting the importance of innovative thinking in civil engineering.

Moreover, the breadth of geosynthetic types, functions, and applications—identified as a challenge earlier in this paper—also provides the appeal of a strong educational foundation for developing tailored solutions to engineering problems. A successful educational experience in this area does more than just transfer technical knowledge; it also helps cultivate professionals capable of critically assessing multiple design alternatives. By evaluating trade-offs involving performance, cost, constructability, and sustainability, students learn to make informed, context-aware decisions—an essential skill for modern engineering practice.

At the same time, the very nature of geosynthetic solutions promotes creativity and intellectual curiosity. Exposure to design challenges that demand novel uses of materials and interfaces encourages students to go beyond readily available design methods and to explore and solve problems. These are the very qualities—resourcefulness, adaptability, and a willingness to innovate—that define successful engineers in a changing infrastructure landscape.

Finally, for educators, integrating geosynthetics into undergraduate teaching provides an opportunity to refresh the curriculum with content that is both modern and engaging. The field's energy and practical importance enable instructors to involve students through design-focused projects, case studies, and applied research, bringing engineering education closer to real-world challenges and opportunities.

4.4. Using Geosynthetics to Strengthen Geotechnical Understanding

Integrating geosynthetics into undergraduate courses does more than introduce a new type of geomaterials; it provides an effective way to improve and deepen students' understanding of fundamental geotechnical concepts. A primary feature of geosynthetics with strong teaching advantages is that their functions (e.g., reinforcement, filtration, barrier) are clearly defined, offering a simple way to illustrate key geotechnical ideas.

For example, geosynthetics offer an excellent opportunity to review and apply concepts related to drainage and flow through porous media, especially when examining the filtration and drainage functions of geotextiles and geonets. Likewise, discussions on reinforcement mechanisms provide a tangible way to revisit the shear strength of soils and the effects of confining stress. In topics like slope stability and retaining structures, incorporating geosynthetics allows students to explore failure modes, load transfer mechanisms, and interface behavior with clarity and a focus on design.

Moreover, the modular and application-oriented nature of geosynthetics education promotes interdisciplinary integration. Concepts from soil mechanics, hydraulics, and environmental engineering

are combined in analyzing geosynthetic barrier systems and reinforced soil structures. As a result, students gain not only exposure to advanced applications but also a deeper understanding of the fundamental principles behind them.

In the words of Prof. Marina Pantazidou, Chair of TC306 (ISSMGE Technical Committee on Geotechnical Education), “Understanding how geosynthetics work together with soils helps me understand better how soils work” (Pantazidou, 2023). Section 7 of this paper will present and discuss educational strategies that illustrate how teaching geosynthetics can enhance the understanding of key geotechnical concepts.

5. Findings from the International Survey on Undergraduate Geotechnical Engineering Education

5.1. Characteristics of Participating Institutions

As previously summarized in Table 2, the survey respondents represented a diverse and well-distributed cross-section of academic institutions within the nine selected countries. The level of engagement was high across regions, with particularly strong participation from countries such as Argentina, Brazil, Canada, Greece, and the USA, all of them with a response rate of about 80% or higher.

The distribution of responses across these countries is shown in Figure 1, which provides a visual summary of institutional participation grouped by program structure (i.e., 4- vs 5-year programs). Among the countries where the undergraduate civil engineering degree is typically completed in four years—namely the United States, Turkey, India, and Canada—the highest number of responses came from the United States (109 responses), representing about 84% of American civil engineering programs. In the group of countries with five-year undergraduate programs—Argentina, Brazil, Colombia, Germany, and Greece—the most responses were from Brazil (44 responses), accounting for about 79% of the Brazilian programs. Although responses from Greece (7 responses) are relatively small, they represent 100% of the civil engineering programs identified in that country.

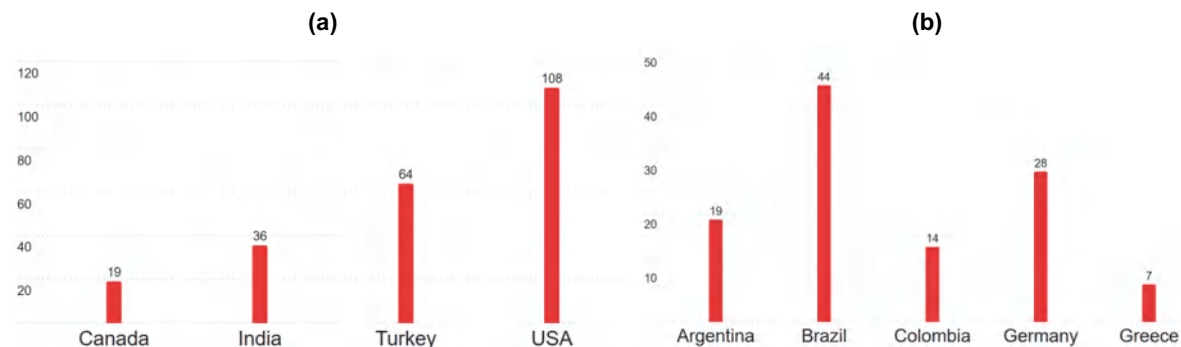


Figure 1. Total number of institutions participating in the educational survey grouped by country: (a) 4-Year Programs; (b) 5-Year Programs

Participating institutions included a mix of large public universities, technical institutes, and private engineering schools, showcasing a variety of curricular structures and educational missions. The language of instruction differed by country, including Spanish, Portuguese, English, German, Greek, and Turkish, highlighting the international scope of civil engineering education in this study. In several instances, programs were offered in more than one language or featured tracks with international accreditation.

Although the main focus of this study is on undergraduate education, responses indicating the highest degree awarded by participating institutions provide useful context for interpreting the survey trends. The vast majority of the participating institutions (86%) offer a Doctorate (Ph.D.) in programs related to geotechnical engineering, while an additional 8% report a Master's degree as the highest credential. Only a small percentage (4%) are programs that only offer undergraduate degrees, and 2% of the respondents indicated other structures. Figure 2 displays the highest degree awarded by participating institutions per country for 4- and 5-year degree programs. The common offering of Ph.D. degrees across both 4-year and 5-year systems indicates that the surveyed institutions generally have a strong academic foundation. The data in Figure 2 thus provide an important basis for understanding future trends in curricular content. Specifically, later comparisons of the number of undergraduate lectures that

include geosynthetics (discussed in subsequent sections) are not expected to be affected by differences in institutional depth or degree capacity.

Overall, the high response rates and broad representation of program types, institutional missions, and national educational standards ensure that the survey's findings can be interpreted within a meaningful global context.

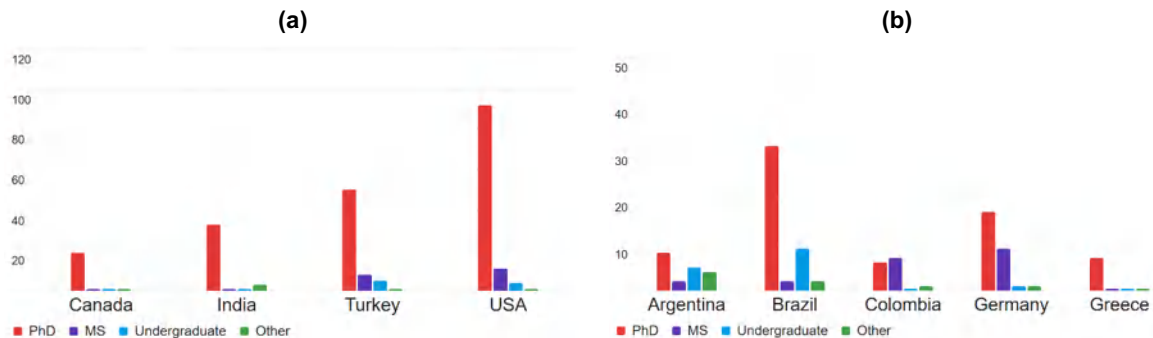


Figure 2. Total number of institutions participating in the education survey, categorized by the highest degree awarded: (a) 4-Year Programs; (b) 5-Year Programs

5.2. The State of Geotechnical Education in Undergraduate Civil Engineering Programs

The survey results provide detailed insight into how many mandatory geotechnical engineering courses are included in undergraduate civil engineering programs across the nine participating countries. These data, presented in **Figure 3**, are critical for understanding whether students are guaranteed exposure to geotechnical content—and, by extension, to geotechnical subfields such as geosynthetics—regardless of institutional or national context. Figure 3a illustrates the distribution of responses from countries with four-year undergraduate programs (United States, Canada, India, and Turkey), while Figure 3b presents the same information for countries with five-year programs (Argentina, Brazil, Colombia, Germany, and Greece).

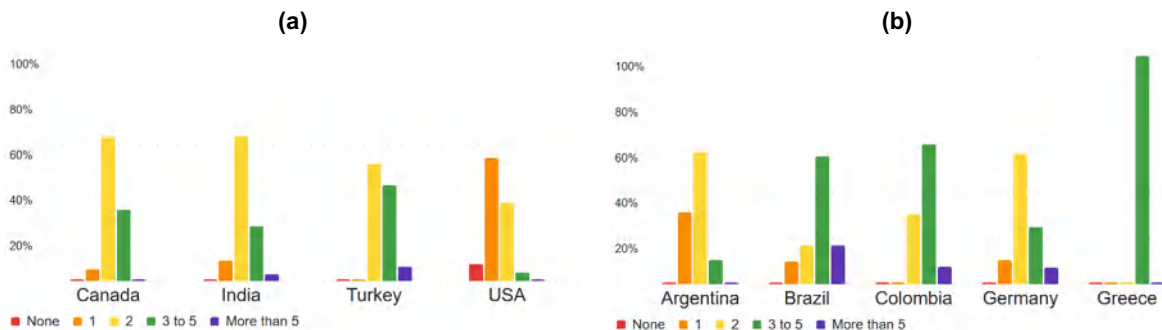


Figure 3. Number of mandatory geotechnical engineering courses: (a) 4-Year Programs; (b) 5-Year Programs

In the 4-year group, Turkey demonstrated a notably strong inclusion of geotechnical engineering in the civil engineering curriculum, with 100% of institutions offering at least two mandatory geotechnical engineering courses, and 48% offering three or more. Canada also shows a strong presence, with 95% of programs requiring at least two mandatory geotechnical engineering courses, and 32% offering three or more. India exhibits similar figures to Canada, with 91% of programs requiring at least two mandatory geotechnical engineering courses, and 27% offering three or more. However, the United States displays a concerning trend, with 7% of participating institutions indicating no mandatory geotechnical engineering courses in their civil engineering programs. This suggests that students from these programs may graduate as civil engineers without having taken a single geotechnical engineering course. Additionally, in the US, only 39% of programs require at least two mandatory geotechnical courses, and just 4% offer three or more. While elective geotechnical engineering courses are generally available in the US programs, the limited number of mandatory courses raises questions about whether students in these programs receive enough exposure to core geotechnical concepts.

In contrast to the 4-year programs, the 5-year programs (Figure 3b) showed a more consistent commitment to geotechnical education. No institution in this group reported the absence of a required

geotechnical course. Greece, for example, reported that 100% of its surveyed institutions offer three to five required geotechnical courses, possibly highlighting a particularly strong national dedication to the field. Colombia also demonstrated a significant inclusion of geotechnical engineering in the civil engineering curriculum, with all institutions offering at least two mandatory geotechnical engineering courses, and 69% offering three or more. Brazil has similar figures to Colombia, with 90% of programs requiring at least two mandatory geotechnical engineering courses, and 73% offering three or more. Germany showed a broader distribution: 89% of the programs offer at least two mandatory geotechnical engineering courses, with 32% offering three or more. The programs in Argentina show a comparatively smaller presence of mandatory geotechnical engineering courses than those in other countries with 5-year programs. Specifically, 68% of the programs offer at least two mandatory geotechnical engineering courses, with only 10% offering three or more.

The comparison between the two groups of countries reveals a predictable yet clear pattern: programs with longer durations tend to include more mandatory geotechnical courses. The only reported instances of programs lacking any such mandatory courses occurred among the 4-year programs (all of which are in the U.S.). While strong geotechnical education is still evident in most 4-year systems, it is within the 5-year structures that the most consistent and intensive coverage of geotechnical content can be observed among required undergraduate coursework.

The gap in geotechnical coverage between 4- and 5-year programs may warrant a call to action within the geotechnical community to reduce adverse educational impacts in geotechnical engineering. This is especially important given a significant global trend: the shortening of civil engineering degree programs. For example, Argentina historically offered six-year civil engineering degrees, which have now been shortened to five years. Colombia, currently offering five-year programs, is considering moving to a four-year model, aligning with other international trends. This shift toward shorter degrees is primarily driven by efforts to harmonize curricula, enhance international mobility, and increase the cost-effectiveness of engineering education (Bonilla-Petriciolet et al., 2021; Nguyen & Habók, 2021).

While this shift may be irreversible, its effects must be approached carefully. When undergraduate programs are squeezed, key subjects like geotechnical engineering risk being marginalized, not because they are unimportant, but due to increased competition for limited curriculum space. It is therefore crucial to stress that certain topics must remain core to all civil engineering programs, regardless of length. Geotechnical engineering—and within this field, geosynthetics—are examples of critical subject areas that should not be postponed to graduate-level education.

The argument that students can simply specialize later through graduate studies (for example, a Master's in Geotechnical Engineering) does not address the core issue. Not all civil engineering students will pursue graduate degrees, and even among those who do, specialization typically happens after their educational paths and professional identities have already begun to form. If foundational exposure to geotechnical topics is missing at the undergraduate level, students might be unprepared to understand or engage with these subjects later. Additionally, topics like geosynthetics are increasingly important across various civil engineering fields—including pavements, environmental containment, and retaining structures—making them relevant to all practicing civil engineers, not just those who decide to specialize.

To complement the analysis of mandatory courses, Figure 4 shows the number of elective geotechnical engineering courses offered by participating institutions. Figure 4a presents the results for countries with four-year programs, while Figure 4b displays the results for countries with five-year programs. In the 4-year group, most (but not all) institutions report offering at least one elective geotechnical course. For instance, in the United States, 8% of programs offer none, 69% offer two or more elective geotechnical courses, and 44% offer three or more. The distribution of elective geotechnical courses is fairly similar among the four countries with 5-year programs evaluated in this study. For example, about half of the programs in each country offer at least three elective geotechnical courses.

The 5-year group, however, shows a more diverse picture. Generally, and perhaps because they offered a larger number of mandatory geotechnical courses compared to the 4-year group, the number of electives in the 5-year group is relatively smaller than in the 4-year group. For example, survey data indicates that 68% of civil engineering programs in Argentina do not offer any elective geotechnical courses. Additionally, 32% of programs in Germany offer no elective geotechnical courses, and 36% of the remaining programs in this country offer only one such elective course. On the surface, these findings might suggest weaker support for geotechnical depth in five-year programs. However, this interpretation would be inaccurate without considering the number of mandatory courses discussed earlier. Conversely, Brazil, Colombia, and Greece provide a relatively strong number of elective geotechnical courses, with 55%, 62%, and 72% of programs in these countries offering at least three geotechnical

technical electives. Notably, 43% of the programs in Greece offer more than five elective geotechnical courses.

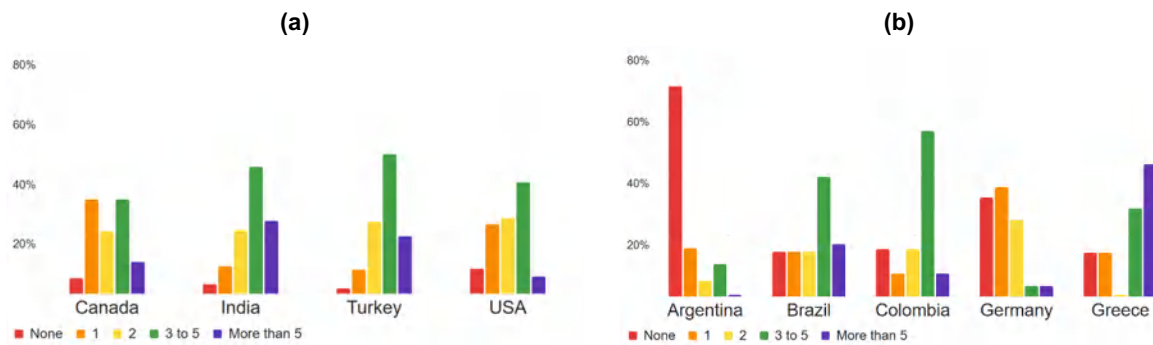


Figure 4. Number of elective geotechnical engineering courses: (a) 4-Year Programs; (b) 5-Year Programs

Indeed, interpreting elective offerings requires context. The survey asked institutions to report the number of elective courses separately from required ones. As a result, the analysis does not directly show whether electives are meant to supplement, complement, or replace core instruction. The trend in the number of elective courses in 4-year programs appears to balance out the number of mandatory courses. For example, in the U.S., the results from Figure 3a indicate that a relatively high percentage (61%) of programs offer one or no mandatory geotechnical engineering courses. This seems to be balanced by a healthy number of electives, with 68% of programs offering at least two elective courses in geotechnical engineering. Conversely, the trend in the number of elective courses in 5-year programs seems inconsistent with the number of mandatory courses. For instance, in Argentina, a high percentage of programs (90%) offer a small number of mandatory courses (two or fewer), yet a large proportion (68%) also offer no elective geotechnical courses. This possibly highlights a lack of opportunities for students to gain foundational geotechnical knowledge. The opposite occurs in Greece, where all programs (100%) include three to five mandatory geotechnical courses, and 43% of programs offer more than five elective courses, indicating particularly strong opportunities for geotechnical engineering education.

Therefore, the most meaningful way to interpret Figure 4 is not by viewing elective courses as standalone indicators of strength or weakness, but by analyzing them alongside mandatory course offerings. Elective geotechnical courses add depth and flexibility to the curriculum, allowing interested students to pursue further specialization. However, they cannot compensate for the lack of fundamental instruction in the required courses. In an era of increasingly compressed undergraduate programs, safeguarding both required and elective opportunities for geotechnical education becomes critical, not only for future specialists but for all civil engineers involved in some form of civil infrastructure design.

5.3. The State of Geosynthetics Education in Geotechnical Courses

The extent to which geosynthetics are incorporated into mandatory undergraduate civil engineering courses varies significantly among the surveyed countries. Figure 5 presents the number of hour-long class sessions in which geosynthetics content is addressed within required coursework. Figure 5a shows the results for countries with 4-year programs (United States, Canada, India, and Turkey), while Figure 5b shows the corresponding data for countries with 5-year programs (Argentina, Brazil, Colombia, Germany, and Greece).

In the 4-year group (Figure 5a), the United States stands out as the country with the lowest level of coverage. A full 71% of institutions report that geosynthetics are not covered at all in any mandatory undergraduate course. Among the remaining programs in the U.S., 21% report 1 hour of coverage and 7% report 2 hours. This suggests that when geosynthetics are included, they are typically introduced in a very limited way—often as part of a single lecture. The coverage of geosynthetics in mandatory courses in the rest of the 4-year programs (Canada, India, and Turkey) is not significantly better than in the U.S. and is quite consistent. Specifically, 58% of institutions in each of these three countries report that geosynthetics are not covered in any mandatory undergraduate civil engineering course.

The 5-year group (Figure 5b) displays more diverse patterns. Brazil clearly leads in geosynthetics coverage in mandatory courses among all surveyed countries. While 20% of Brazilian programs report no mandatory coverage, the rest show a broad range: 29% report 1 hour, 17% 2 hours, 24% 3 to 5 hours, and notably, 10% of programs (4 institutions) report more than 5 hours of geosynthetics instruction in required geotechnical engineering courses. This reflects a strong and growing recognition

of the importance of geosynthetics within Brazil's undergraduate civil engineering education. Argentina also shows meaningful inclusion, with 42% of programs reporting 2 hours, and another 26% reporting 3 to 5 hours. In Colombia, 46% of programs report 1 hour, but about one-third of institutions (31%) indicate that geosynthetics are not covered in any required course. Germany and Greece, despite offering relatively healthy offerings in terms of the number of mandatory undergraduate geotechnical engineering courses, exhibit the lowest inclusion among the 5-year countries: 64% of German institutions and 86% of Greek institutions report no coverage of geosynthetics in required geotechnical coursework.

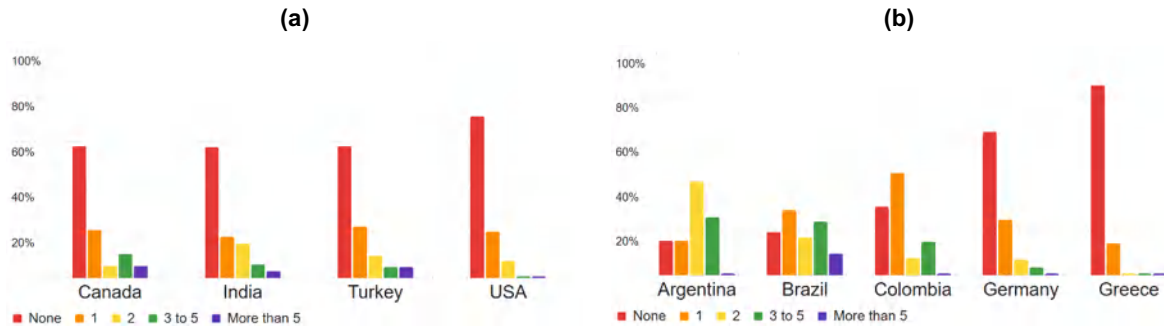


Figure 5. Number of hour-long classes that include geosynthetics in mandatory courses: (a) 4-Year Programs; (b) 5-Year Programs

The comparison between Figures 5a and 5b reveals several important insights. First, the length of the program does not seem to be a dependable predictor of whether geosynthetics will be included in the required geotechnical courses. While it might be expected that 5-year programs would have more room to incorporate specialized content, this is not consistently the case. In fact, some of the lowest inclusion rates (e.g., Germany and Greece) are observed in countries with a strong number of mandatory courses. Conversely, several 4-year countries (e.g., Canada, India, and Turkey), despite their limited curricular space, show that 42% of their programs provide at least one hour of geosynthetics instruction in their required geotechnical engineering courses.

It seems that the key difference is not in program length but in curricular priorities and institutional emphasis. Among all countries, Brazil stands out as the most comprehensive in incorporating geosynthetics into required undergraduate courses, both in the number of programs that include the topic and in the depth of instruction provided. This demonstrates not only a curricular focus on geotechnical issues but also an obvious institutional recognition of the practical importance of geosynthetics in civil engineering applications.

These findings strengthen an important argument for geosynthetics education: it should not be considered an advanced or optional subject to be reserved for elective courses or postgraduate specialization. Instead, geosynthetics are a crucial part of modern geotechnical engineering, relevant to fundamental topics like slope stability, retaining structures, pavement design, and environmental containment. The lack of geosynthetics in required undergraduate courses means many civil engineers will graduate without even a basic knowledge of materials and systems they are likely to face in practice.

The data from Figures 5.5a and 5.5b, therefore, highlight an important challenge: ensuring all students, regardless of institutional context or program length, receive at least minimal, meaningful exposure to geosynthetics as part of their required civil engineering education. This goal is essential not only for promoting technical competence but also for making sure that future engineers are prepared to make informed decisions about a class of materials that continues to grow in relevance and application.

Complementing the analysis of required coursework, Figure 6 shows the number of hour-long sessions dedicated to geosynthetics within elective undergraduate courses. While elective offerings allow for deeper exploration of specialized content, they do not guarantee universal exposure. In the 4-year group (Figure 6a), Canada and U.S. stand out with a sizable number of programs that offer no geosynthetics coverage among the elective geotechnical courses (53% and 40%, respectively), yet a nonnegligible number of programs offer at least 6 hours of geosynthetics coverage among the elective geotechnical courses (27% and 12%, respectively). India stands out among the countries in this group by having possibly the largest covering of geosynthetics in elective courses (at least 60% of the institutions offer 3 or more hours of geosynthetics coverage in these courses).

In the 5-year group (Figure 6b), the number of institutions that do not offer any geosynthetics coverage in their elective courses is staggering: 84% in Argentina, 79% in Germany, 43% in Greece, 32% in Brazil, and 31% in Colombia. On the more positive side, Greece and Brazil have the highest percentages (43%

and 37%, respectively) of institutions that offer at least 3 hours of geosynthetics in their elective geotechnical courses. These data confirm that elective courses can enhance the curriculum but cannot replace the guaranteed instruction provided through required coursework. Ensuring that geosynthetics is incorporated into the core curriculum remains essential to prepare all students—not just those pursuing specialized tracks—for the demands of modern geotechnical practice.

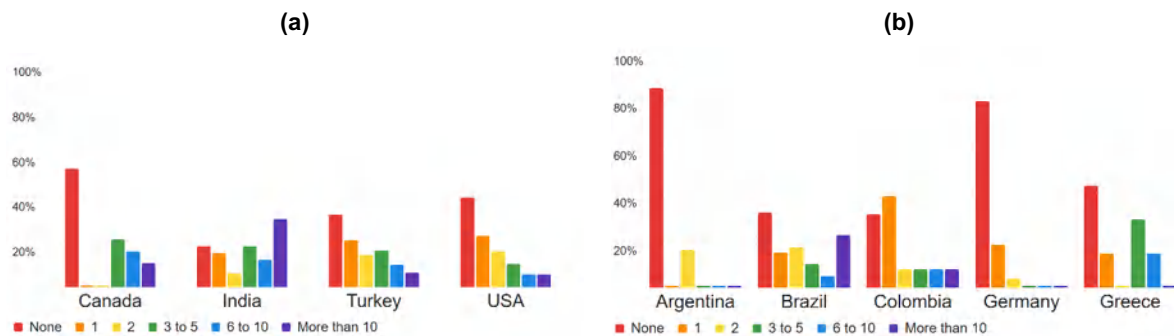


Figure 6. Number of hour-long classes that include geosynthetics in elective courses: (a) 4-Year Programs; (b) 5-Year Programs

6. Institutional Tools for Integrating Geosynthetics in the Classroom

6.1. The International Geosynthetics Society (IGS)

The International Geosynthetics Society (IGS) has served as the main global organization dedicated to advancing geosynthetics in engineering, education, and research. Founded in 1983 in Paris as the International Geotextile Society, the IGS expanded its scope to include all geosynthetic materials, leading to its current name adopted in 1994. This change reflected the diversification of geosynthetics themselves—from geotextiles to a broad range of engineered polymer products, each providing unique functions in geotechnical, hydraulic, and environmental applications.

IGS has expanded into a global organization with over 3,000 members through a network of national and regional chapters. Its governance structure—led by a democratically elected council—ensures international representation and stability. The society offers a platform for dialogue and knowledge sharing among researchers, practitioners, educators, and industry stakeholders across all continents. A key role of IGS is disseminating knowledge through activities like sponsoring two leading peer-reviewed journals—Geotextiles & Geomembranes and Geosynthetics International—and organizing the quadrennial International Conference on Geosynthetics, regional conferences, and technical workshops. Its support for technical committees focused on specialized areas such as soil reinforcement, barrier systems, and sustainability is equally vital. These activities not only produce state-of-the-art documents but also promote international technical collaboration.

Education has been a core mission of the IGS for a long time. Starting in the 2000s, the Society introduced student memberships, encouraged young professionals to get involved through awards, and conducted outreach to promote geosynthetics education. Additionally, the IGS has worked with standards organizations like ASTM/D35 and ISO/TC 221 to develop terminology, testing procedures, and design guidelines that support consistent global adoption.

Together, these activities reinforce IGS's core purpose: to provide understanding and promote the appropriate use of geosynthetic technology worldwide. This institutional foundation—combining scholarly publishing, global conferences, technical guidance, and student outreach—has enabled the launch and success of targeted educational programs. Chief among these is the Educate-the-Educators (EtE) initiative, which is discussed in the next section.

6.2. The IGS' Educate-the-Educators (EtE) Program

To address potential challenges of teaching geosynthetics in undergraduate civil engineering programs, the International Geosynthetics Society (IGS) launched the Educate-the-Educators (EtE) initiative in 2013. Designed to empower university faculty—especially those unfamiliar with geosynthetics—this program provides both technical content and pedagogical strategies needed to incorporate geosynthetics instruction into existing engineering curricula (Zornberg et al., 2020; Gardoni et al., 2024).

The inaugural EtE event was held in Argentina, and the model has since been successfully replicated across many countries and continents.

The EtE initiative was created to fill a perceived educational gap: most undergraduate civil engineering students graduate with minimal or no exposure to geosynthetics, despite their widespread application in infrastructure design and construction. This problem is compounded by a generational knowledge gap—many faculty currently teaching geotechnical courses were never trained themselves in geosynthetics (Zornberg et al., 2020). The EtE program directly tackles this dual challenge by offering instructors modular, ready-to-use content that can be tailored to different institutional contexts.

Each EtE event usually includes an intensive, multi-day workshop that combines theoretical lessons, hands-on demonstrations, and curricular planning. Participants receive a variety of resources—including slide decks, design examples, case histories, and physical samples of geosynthetics—to help incorporate the material into the classroom with minimal preparation. A fundamental idea of the initiative is that even just one hour of geosynthetics instruction, if given to all civil engineering undergraduates, can significantly improve their professional readiness (Zornberg et al., 2020). Events also provide opportunities for more advanced implementations, such as creating elective courses and graduate-level modules.

Follow-up assessments, especially those in Brazil, demonstrated the program's effectiveness. As of June 2025, 30 EtE events had been held in 21 countries, reaching over 800 university professors. Survey data from these events show that between 60% and 90% of attendees incorporated geosynthetics into their courses, and 10% to 17% went further to develop standalone instructional modules (Gardoni et al., 2024). Instructors have also expanded the program's reach by organizing local seminars, delivering public lectures, or advising government agencies on curriculum development.

EtE workshops are funded by IGS and local chapters. They cover instructor costs, accommodation, and materials, with participants only covering their travel. The workshops involve local geosynthetics industry partners to facilitate practical product identification sessions and real-world case discussions. Recognizing the need for ongoing support, the IGS Foundation, established in 2021, has coordinated complementary funding.

The EtE initiative serves as a model for how professional societies can drive educational change. By connecting technical content with scalable implementation methods, the IGS has developed a program that not only fills a specific curriculum gap but also builds a global community of educators dedicated to modernizing geotechnical teaching.

7. Strategies for Teaching Geosynthetics in Undergraduate Education

7.1. Provide Early Exposure to Geosynthetics as a Core Geotechnical Material

One key strategy promoted in this paper is to introduce students to geosynthetics early in their education, typically during the mandatory introductory course for all civil engineering undergraduates. Incorporating geosynthetics into this course, which often emphasizes soils as a primary material, helps students see these materials not as optional or secondary, but as core geomaterials in geotechnical engineering. This first exposure provides a conceptual foundation for understanding the mechanical and hydraulic properties of geosynthetics alongside soils, promoting early comparisons and a more integrated understanding.

The first geotechnical engineering course in most civil engineering programs functions as a “materials” course, introducing students to the engineering behavior of an essential civil engineering material: soils. The proposal here is not to shift the course's purpose toward geotechnical applications or design but to slightly broaden its scope to include synthetic geomaterials as part of the same foundational framework. Geosynthetics, alongside soils, should be presented as essential construction materials within the geotechnical engineer's toolkit. As highlighted by the findings from the survey conducted in this study (see Section 5.3), this introductory course may be the only chance for all civil engineering students—including those who will not pursue geotechnical electives—to be exposed to geosynthetics. In many academic programs, particularly in the United States, this single course is the only required geotechnical instruction, making it crucial to maximize that opportunity.

Currently, when geosynthetics are introduced at the undergraduate level, it typically occurs in geotechnical “applications” or within design-focused electives. This approach introduces geosynthetics late in the curriculum—if at all—and misses the chance to connect their properties and functions with fundamental soil mechanics instruction. Conversely, introducing them early enables teaching geosynthetics alongside core geotechnical concepts. For example, students can draw parallels between

the tensile behavior of geogrids and the frictional resistance of soils or between the filtration function of geotextiles and that of granular materials. Survey results in Section 5.3 further support that, when included, geosynthetics are included in the curriculum, this often occurs in elective courses not taken by all students, contributing to uneven exposure even within the same academic institution.

Introducing geosynthetics early also helps clarify the concept of “functions” in geotechnical materials, an idea central to performance-based design that students will encounter later in the curriculum. While students near the end of their introductory geotechnical engineering course have been exposed to a wide range of soil properties—from physical properties like specific gravity, to compositional ones such as plasticity index, to hydraulic properties like saturated hydraulic conductivity, and to mechanical properties like compression index and effective friction angle—these are rarely presented as ways to meet specific geotechnical functions. Unlike soils, geosynthetic properties are introduced through their engineered functions: separation, reinforcement, stiffening, filtration, barrier, drainage, and protection. Recognizing these functions (for both natural and synthetic geomaterials) gives students a framework for choosing material properties based on the intended use. Ultimately, this view can help students better understand the functional role of natural geomaterials (i.e., soils themselves) and serve as a pedagogical entry point for gaining deeper insight into the role of both synthetic and natural geomaterials in the built environment.

Importantly, incorporating geosynthetics into the introductory geotechnical course does not require extensive coverage. Even a single hour-long lecture, delivered to all undergraduate students, can establish foundational awareness. Though modest in duration, this exposure can have a far-reaching impact: ensuring that every graduating civil engineer—regardless of future specialization—leaves with basic knowledge of a class of materials central to modern infrastructure practice. Sensitive to the curricular challenges in civil engineering programs (see discussion in Section 4.2), this recommendation considers key constraints, such as limited instructional time, rigid curricula, and the competing demands of accreditation standards. To assist with implementation, the International Geosynthetics Society (IGS) offers a fully developed one-hour lecture on geosynthetics, complete with slides and a recorded presentation, freely available through its website (Zornberg, 2021). For courses that include laboratory sessions, simple experiential activities—such as tactile identification of different geosynthetic products—can also be integrated, as outlined on the IGS experiential learning webpage. Even brief, well-placed exposure to foundational concepts can lead to long-term retention and understanding, especially when aligned with core learning principles that emphasize early activation of prior knowledge and relevance (Ambrose, 2020).

Survey findings (Section 5.3) emphasize the importance of early inclusion: geosynthetics are often left out of required coursework, especially in four-year programs. Exposure is usually limited to electives, which many students never choose. This fragmented approach creates widespread gaps in preparedness. Introducing geosynthetics in the initial geotechnical course addresses this issue by presenting them not as secondary topics, but as vital geotechnical materials that all civil engineers need to understand.

7.2. Emphasize the Role of Geomaterials as Essential “Construction” Materials

By the end of the introductory geotechnical engineering course, students usually realize that soils, unlike materials such as concrete or steel, are not manufactured to uniform standards. Instead, soils are natural geomaterials with high variability and site-specific properties. This variability requires careful experimental characterization, as each soil is essentially unique. Consequently, much of geotechnical education focuses on learning how to classify, test, and interpret soil behavior, highlighting the importance of tailored assessments for both design and construction.

However, the characterization of geomaterials goes beyond simply analyzing the subsurface conditions that support structures, such as a building’s deep foundation system. In addition to their structural support role, soils and other geomaterials are frequently used as construction materials in civil engineering projects, like building earth dams, embankments, and waste containment systems. Recognizing this dual purpose is essential. The idea of using soil as a construction material may have been touched upon in introductory courses, typically in the context of compaction. However, students may not fully appreciate how frequently and fundamentally geomaterials are selected, processed, and placed for construction purposes. This includes sourcing from borrow pits, assessing suitability, and sometimes modifying or blending materials based on availability, transportation distance, and performance needs.

The discussion of geosynthetic functions offers a teaching entry point to highlight the role of geomaterials in construction. When students learn how geosynthetics are chosen for specific functions, they start to

see similarities with how soils must be selected and placed to meet the same performance goals. Although it may seem obvious that geomaterials like gravel, clay, sand, or geotextiles are not interchangeable, the idea of "functions" helps clarify why careful material specifications are needed to ensure that differences among geomaterials are expressed through relevant properties, leading to the construction of a geotechnical system that performs as intended.

A useful example comes from the function of separation. This function, often fulfilled by geotextiles, involves preventing the mixing of dissimilar soils, such as a clean granular base layer overlying a soft clay subgrade in road construction. Intermixing may significantly compromise the performance of the granular base by lowering its shear strength, drainage ability, and long-term stability. Understanding geosynthetics highlights the importance of preventing such mixing, a concern relevant to many geotechnical systems. However, this idea—that different soils fulfill distinct functions and should often be kept apart—is seldom emphasized in introductory courses, despite its crucial role in real-world geotechnical construction.

Another instructive example is the barrier function, especially in the context of hydraulic containment systems used in landfills, tailings dams, and water retention structures. Historically, compacted clay has been the natural material of choice for creating low-hydraulic-conductivity barriers. However, the advent of geosynthetics such as geomembranes and geosynthetic clay liners (GCLs) has broadened the range of materials available for this purpose. In fact, the most effective barrier systems are composite barriers—systems that combine a geomembrane with a compacted clay layer. The intimate contact between these materials minimizes leakage and provides redundancy in containment, significantly improving their long-term performance. The synergy between natural and synthetic geomaterials is well established in the literature; Giroud and Bonaparte (1989) identified composite liners as best practice for minimizing leakage in containment applications.

Recognizing geomaterials as functional construction materials—whether natural or synthetic—gives students a more accurate and practice-oriented view of geotechnical engineering. It highlights that material selection is not just about classification or compliance, but about purpose, performance, and compatibility. Introducing this mindset early in the curriculum helps students gain a deeper understanding of how geotechnical systems are assembled, why material interfaces matter, and how design choices are influenced by both natural variability and engineered solutions. In this context, geosynthetics serve not only as high-performance materials but also as educational tools that explain the construction role of all geomaterials in civil infrastructure.

7.3. Draw Parallels between Geosynthetics and Soil Mechanics Principles

Core concepts in teaching synthetic geomaterials (geosynthetics) closely resemble those of earthen geomaterials such as soils and rocks. Many mechanical and hydraulic principles used to analyze and design soils are equally applicable to geosynthetics. This conceptual similarity offers valuable teaching opportunities. Educational modules on material properties can emphasize clear similarities between the behaviors of geosynthetics and core principles of soil mechanics, improving student understanding through side-by-side comparison.

The functional use of both natural and synthetic materials in applications related to drainage, filtration, and stiffening can provide a natural basis for reinforcing traditional geotechnical engineering concepts. These functions can be explained using terms familiar to students from previous lectures. For instance, designing drainage systems with soils and geosynthetics draws directly on the concept of hydraulic conductivity; filtration relates to cross-plane flow; and stiffening involves increasing confinement within the soil mass, directly influencing shear strength and modulus. These parallels not only improve technical understanding but also encourage a systems-level perspective on how different geomaterials interact in the built environment, a pedagogical approach grounded by evidence showing that connecting new material to students' prior knowledge significantly enhances learning outcomes (Ambrose, 2020).

A particularly effective teaching opportunity arises from the drainage function of geosynthetics, which can be used to revisit in-plane flow governed by Darcy's Law. Traditionally, this principle is introduced by analyzing flow through soil layers. However, the same governing relationship applies to geosynthetics, with minor modifications in terminology. Figure 7 shows the actual slide used to introduce the concept of in-plane drainage in an introductory geotechnical engineering class. For flow through a soil layer of thickness t , Darcy's Law is expressed as:

$$Q = k_p \cdot \frac{\Delta h}{\Delta l} \cdot w \cdot t \quad (1)$$

where Q is the total flow rate, k_p is the in-plane hydraulic conductivity of the medium, $\Delta h/\Delta l$ is the hydraulic gradient, w is the width of the drainage path, and t is the thickness of the layer. As shown in the figure, this could be rewritten as:

$$Q = \theta \cdot i \cdot w \quad (2)$$

where θ is the transmissivity of the geosynthetic and i is the hydraulic gradient. Transmissivity itself is defined as:

$$\theta = k_p \cdot t \quad (3)$$

This parallel structure allows students to see how traditional fluid flow concepts carry over to geosynthetic materials. By presenting these formulations together, instructors can reinforce the underlying physics of seepage while simultaneously introducing terminology specific to geosynthetics.

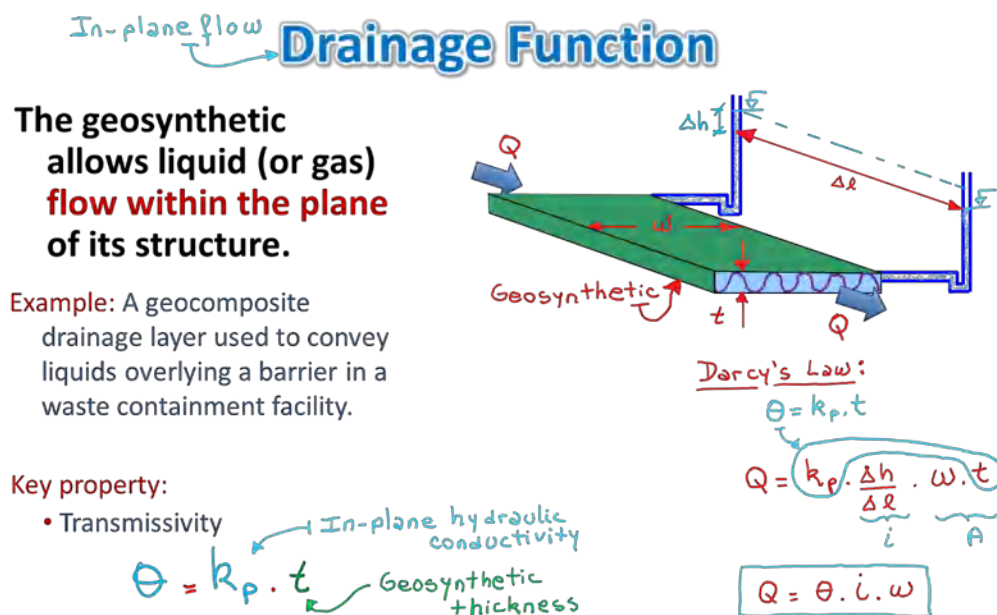


Figure 7. Slide illustrating the drainage function in a geosynthetics lecture, focusing on complementing earlier content in a typical introductory geotechnical engineering course

A similar opportunity arises when discussing the filtration function of geosynthetics, which involves cross-plane flow and leads to the definition of permittivity. Figure 8 shows the slide used for this concept in an introductory geotechnical engineering class. Again, Darcy's Law applies, but for flow normal to a geosynthetic layer, we'll have:

$$Q = k_n \cdot \frac{\Delta h}{t} \cdot A \quad (4)$$

where k_n is the cross-plane hydraulic conductivity of the material, Δh is the head difference, t is the thickness, and A is the cross-sectional area normal to flow. For ease of characterization in thin manufactured products, the concept of permittivity (ψ) is introduced:

$$\psi = k_n/t \quad (5)$$

This leads to the commonly used flow expression for geosynthetics:

$$Q = \psi \cdot \Delta h \cdot A \quad (6)$$

Permittivity is a standard property in geosynthetics testing, commonly reported in product datasheets. Teaching this relationship allows students to strengthen their grasp of Darcy's Law while introducing the hydraulic parameters used in geosynthetics characterization. The consistent mathematical framework helps unify traditional flow concepts with relevant characterization of geosynthetics properties.

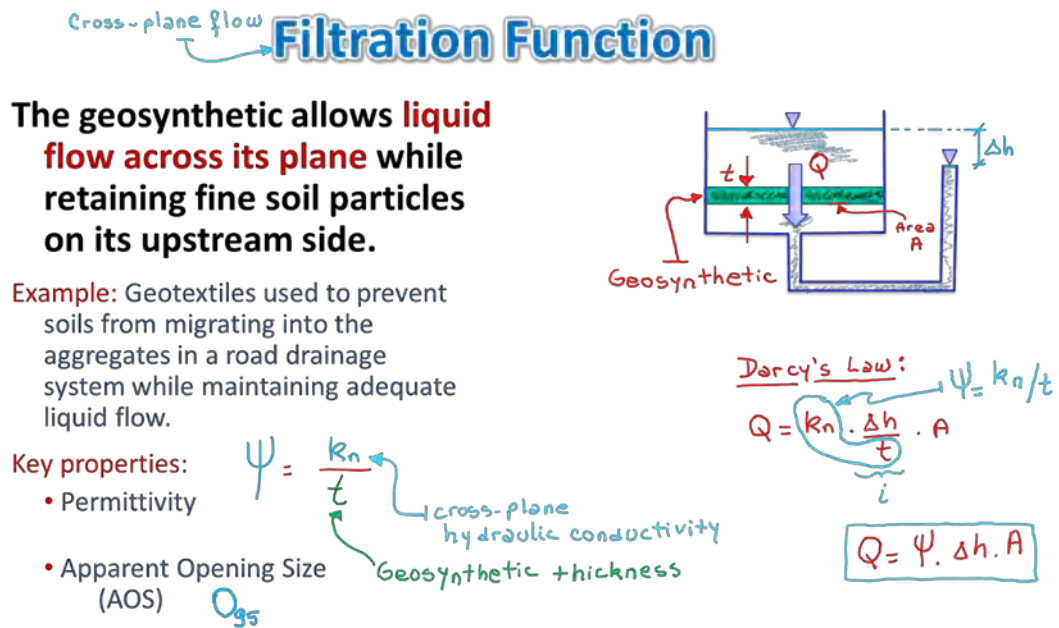


Figure 8. Slide illustrating the filtration function in a geosynthetics lecture, focusing on complementing earlier content in a typical introductory geotechnical engineering course

A third instructive example emerges from the stiffening function of geosynthetics. This concept is not directly addressed in standard geotechnical curricula, yet it highlights an important mechanical principle: the confinement sensitivity of granular soils. Specifically, discussing the stiffening function allows highlighting how granular soils exhibit excellent mechanical behavior—high shear strength and modulus—but only when confined. Using geosynthetics, especially in applications like geogrid-stabilized pavements or geocell-reinforced bases, provides lateral restraint that improves confinement. This leads to increased modulus, improved load distribution, and reduced permanent deflections.

Introducing the stiffening function of geosynthetics helps students visualize and quantify how confinement affects soil behavior. It also links soil mechanics concepts like shear strength and modulus to system-level thinking about load transfer. This integrated view aids students in understanding how engineered solutions, such as geosynthetic stabilization, are rooted in fundamental soil behavior and can be optimized through proper interaction between materials.

In summary, teaching geosynthetics offers a unique opportunity to reinforce, expand, and unify traditional soil mechanics principles within a practical context. Whether through fluid flow equations that govern drainage and filtration or the mechanical frameworks that underpin modulus and confinement, geosynthetics help revisit fundamental principles from a slightly different perspective. Including them in geotechnical education not only familiarizes students with geosynthetics but also enhances their understanding of core soil mechanics concepts. In other words, geosynthetics are not just supplementary materials—they act as an effective lens for teaching essential geotechnical concepts clearly and powerfully.

7.4. Highlight the Two-Dimensional Nature of Most Geosynthetics

One of the distinguishing characteristics of most geosynthetics is their two-dimensional shape. Unlike natural soils, which are usually described based on their volumetric properties, geosynthetics are often so thin that their thickness is ignored or included within other parameters. This difference affects how material properties are defined and measured. For example, geosynthetics used for drainage and filtration usually do not report hydraulic conductivity and thickness separately; instead, they report transmissivity or permittivity—properties that include thickness implicitly. As discussed earlier in Section 7.3, this adjustment does not change the fundamental principles, such as Darcy's Law. However, students should understand that geometry and scale affect how those principles are used in geotechnical practice.

Consider again the drainage function. As discussed in Section 7.3, in-plane fluid flow in soils is usually described using Darcy's Law, with hydraulic conductivity (k_p) and layer thickness (t) used to characterize the medium. For thin geosynthetics such as geonets and geocomposites, this principle remains but is

adapted using transmissivity (θ), which simplifies the representation by including thickness implicitly. Referring back to Equation 3, this adaptation emphasizes how the two-dimensional nature of geosynthetics influences parameter definition while maintaining key hydraulic principles.

A similar logic applies to the filtration function, which involves cross-plane flow. As described earlier in Section 7.3 (see Equation 5), permittivity (ψ) characterizes thin geosynthetic materials by normalizing cross-plane hydraulic conductivity with thickness. This enables consistent characterization without relying on explicit thickness measurements, demonstrating how geosynthetics adapt classical hydraulic concepts to their physical geometry.

The reinforcement function of geosynthetics offers another opportunity to connect foundational mechanics concepts with geosynthetic behavior. Figure 9 displays the actual slide used to introduce reinforcement concepts in an introductory geotechnical engineering class. Hooke's Law, which governs traditional stress-strain relationships in elastic materials, can be expressed as:

$$\sigma = \frac{F}{w \cdot t} = E \cdot \varepsilon \quad (7)$$

where σ is the normal stress, F is the applied force, $w \cdot t$ is the cross-sectional area, E is Young's modulus, and ε is strain. However, for geosynthetics, this relationship is often reformulated to use "unit tension" (T), defined as force per unit width [F/L], making it more suitable for two-dimensional materials such as geosynthetics:

$$T = J \cdot \varepsilon \quad (8)$$

Here, J is the tensile stiffness, which equals the product of E and the geosynthetic thickness. By replacing the use of stress (force per unit area) with unit tension (force per unit length), this approach aligns with the two-dimensional geometry of geosynthetics. This transformation helps students bridge familiar concepts from solid mechanics to new applications in geotechnical engineering, emphasizing how dimensionality affects material modeling.

Reinforcement Function

**The geosynthetic develops tensile forces intended to
maintain or improve the stability of the soil-geosynthetic
composite.**

Example: Geosynthetics used to increase the margin of safety of a steep earth slope.

Key properties:

- Ultimate tensile strength T_{ult}
- Interface shear strength δ, P_r
- Reduction factors:
 - Creep RF_{cr}
 - Installation damage RF_{ID}
 - Durability RF_D

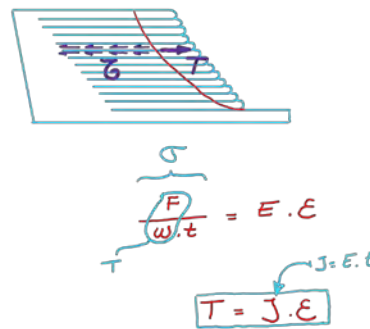


Figure 9. Slide illustrating the reinforcement function in a geosynthetics lecture, focusing on complementing earlier content in a typical introductory geotechnical engineering course

In conclusion, explicitly teaching the two-dimensional nature of geosynthetics helps prevent terminology differences from hiding the fact that the fundamental engineering principles behind the mechanical and hydraulic behavior of soils and geosynthetics are the same. Whether through transmissivity and permittivity in fluid flow or tensile stiffness in reinforcement, geosynthetics continue to use classical laws while adapting them to their unique features. Emphasizing these adaptations promotes a better understanding of how the geometry of geomaterials can influence material characterization, while ensuring that terminology differences do not obstruct the essential knowledge needed for working with both traditional and modern materials in geotechnical practice.

7.5. Revisit the Geosynthetic “Materials” Concepts in Later “Application” Courses

As shown by the survey findings on the state of geosynthetics education in undergraduate geotechnical courses (see Section 5.3), instruction on geosynthetics most often occurs in elective classes, usually focused on geotechnical design applications. This common practice should definitely continue, even as this paper recommends introducing geosynthetics earlier in the curriculum, specifically in the initial course that covers natural geomaterials (i.e., soils). The proposed approach does not replace the vital role of elective, application-oriented courses in reinforcing geosynthetics concepts. Instead, it ensures that when students take these advanced courses, geosynthetics will no longer be their first exposure to the topic.

This sequencing provides a significant pedagogical benefit. Instructors teaching application-oriented topics in geotechnical design won't need to pause to introduce the types, properties, and functions of geosynthetics from the beginning. Instead, these fundamental material concepts will already have been introduced, just as core soil mechanics principles would have been covered earlier in the curriculum. A quick review of geosynthetics—similar to the review often given for shear strength, hydraulic conductivity, or soil consolidation—will be enough to prepare students for more advanced, practical geotechnical subjects.

For example, when teaching the design of earth retaining structures, it would be pedagogically improper to introduce the topic of shear strength for the first time within the design module. Instead, instructors usually assume a working understanding of shear strength and focus on concepts like earth pressure theory and stability. A similar approach applies when discussing reinforced soil structures. Instructors should be able to assume that students are already familiar with the existence of geogrids and the reinforcement function of geosynthetics. Instruction can then concentrate on integrating these concepts into design frameworks—such as internal and external stability of mechanically stabilized earth (MSE) walls—rather than diverting time on basic definitions.

In summary, revisiting geosynthetics in upper-level geotechnical courses enables deeper engagement with their applications instead of just reviewing material fundamentals. This progression mirrors the way soils are treated in the curriculum: introduced early as materials and revisited later in design contexts. Such sequencing aligns with the cognitive framework highlighted in learning research, where spaced repetition and revisiting concepts in varied contexts enhance mastery and long-term transferability (Ambrose, 2020). Integrating geosynthetics into this same pedagogical structure reinforces their role as core geotechnical materials and ensures students are prepared to use them effectively in professional practice.

8. Conclusions and Final Remarks

This paper highlights the urgent need to include geosynthetics in undergraduate civil engineering curricula and offers practical strategies for implementation. Based on both educational principles and institutional realities, the paper shows how geosynthetics—already essential in geotechnical engineering—can be effectively introduced to students early in their academic journey. It recommends presenting geosynthetics as part of the broader family of geomaterials, alongside soils, to ensure that students receive a well-rounded understanding of geotechnical materials and their engineering applications.

A key argument in this paper is that geosynthetics should no longer be treated as peripheral or elective content in civil engineering education. Their extensive use in modern infrastructure, inclusion in design standards, and increasing importance for sustainable engineering practices necessitate their presence in core geotechnical instruction. Introducing geosynthetics early—especially in the first geotechnical class—gives students exposure to new materials and opportunities to strengthen their grasp of fundamental geotechnical principles. The field of geosynthetics includes a wide variety of materials and functions, which presents an educational challenge but also provides a great chance to foster creativity in engineering design. Ultimately, it can be concluded that:

Because of the breadth in geosynthetics, a successful learning experience will produce professionals who value careful assessment of alternatives to make their best engineering choices.

Because of the ingenuity of engineering solutions involving geosynthetics, a successful learning experience will produce professionals who value creativity and discovery.

This study involved the development, implementation, and analysis of a comprehensive international survey targeting geotechnical engineering faculty in nine countries—Argentina, Brazil, Canada, Colombia, Germany, Greece, India, Turkey, and the United States—covering both 4-year and 5-year undergraduate degree programs. With an approximate response rate of 72% from 466 identified civil engineering programs, the survey provides a solid and representative overview of how geotechnical

education is organized worldwide. It examined the inclusion of geosynthetics in curricula, the structure of required and elective courses, and faculty perspectives on the challenges and opportunities in teaching this subject. The main findings from this study can be summarized as follows:

- The survey received a high response rate—73% overall—across nine countries and 339 civil engineering programs, ensuring strong representation from both 4-year and 5-year educational systems.
- In 4-year programs, over half of the institutions offer at most only one mandatory geotechnical engineering course, and some offer none at all.
- In 5-year programs, such as those in Brazil and Greece, geotechnical engineering is consistently part of the required curriculum, often with multiple courses.
- Across all surveyed programs, over half of future civil engineers do not receive even a single hour of instruction on geosynthetics within required courses.
- When available, coverage of geosynthetics in elective geotechnical courses is typically limited to a few hours, and some programs offer no exposure at all.

Additional findings can be drawn from the implementation of Institutional Tools. Specifically:

- The International Geosynthetics Society (IGS)'s Educate-the-Educators (EtE) initiative has been successful in addressing the lack of faculty preparation, having trained over 800 professors in over 16 countries.
- Follow-up assessments in countries such as Brazil indicate that 60% to 90% of EtE participants incorporated geosynthetics into their courses, with 10% to 17% developing full instructional modules.

Important additional findings can be drawn from the evaluation of the proposed educational strategies to implement geosynthetics in undergraduate curricula, as follows:

- Introducing geosynthetics in the first geotechnical engineering course is expected to ensure that all students, including those not pursuing geotechnical electives, receive foundational exposure to these materials.
- Emphasizing the role of geomaterials as construction materials helps clarify how both natural and synthetic geomaterials are selected, specified, and used in infrastructure systems.
- Drawing parallels between geosynthetics and classical soil mechanics concepts could be identified to enhance the teaching of hydraulic and mechanical behavior by providing relatable, engineered analogues.
- Highlighting the two-dimensional nature of geosynthetics—through concepts like transmissivity, permittivity, and stiffness—may provide a valuable lens for reinforcing core engineering principles in new contexts.
- Revisiting geosynthetics in application-focused courses later in the curriculum allows for deeper engagement with design, rather than requiring remedial instruction on material fundamentals.

Overall, the results from the international survey and the strategies suggested to introduce undergraduate students to geosynthetics indicate a practical and effective pathway that can help modernize civil engineering education. These insights emphasize the importance and practicality of integrating geosynthetics meaningfully into the core curriculum, ensuring that all students—regardless of specialization—are better equipped for the demands of modern geotechnical practice.

Ultimately, the power behind learning geosynthetics may stem precisely from their challenging breadth and their appealing ingenuity. Through this dual lens, students develop not only technical competence but also the capacity to evaluate engineering alternatives critically and creatively.

Acknowledgements

The author gratefully acknowledges the assistance of several colleagues who contributed to the international survey on geosynthetics education by helping identify key contacts and providing relevant information about their respective countries. Special thanks go to Prof. Virginia Sosa (Argentina), Prof. Marolo Alfaro (Canada), Prof. Mario Ramirez (Colombia), Prof. Ennio Palmeira (Brazil), Prof. Gerhard Brau (Germany), Prof. Marina Pantazidou (Greece), Prof. Jagdish Shahu (India), Prof. Nejan Huvaj (Turkey), and Prof. Kristin Sample-Lord (United States) for their invaluable support.

The author also wishes to thank the members of the International Geosynthetics Society (IGS) for their ongoing commitment and collaboration in supporting the Educate-the-Educators (EtE) program. He specifically acknowledges the important contributions of Sam Allen, Augusto Alza, Madalena Barroso, Richard Brachman, Barry Christopher, Ivan Damians, Graça Gardoni, Patricia Guerra-Escobar, Ennio Palmeira, Marina Pantazidou, Victor Pimentel, Boyd Ramsey, Rosemberg Reyes, and Delma Vidal. The

success of the EtE program has been made possible by the dedication of these individuals and many others who have contributed their time and expertise to advance geosynthetics education worldwide.

References

- ABET (2022). Criteria for Accrediting Engineering Programs, 2022–2023. Engineering Accreditation Commission. <https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2022-2023/>
- Ambrose, S. A. (2020). Common Instructional Practices Grounded in Evidence. Proceedings of the International Conference on Geotechnical Engineering Education 2020 (GEE2020), June 24–25, Athens, Greece.
- Bonilla-Petriciolet, A., Camarena, M.V., Guerra-Sánchez, R. (2021). Engineering Education Reform in Latin America: Challenges and Perspectives. *International Journal of Engineering Education*, 37(5), 1124–1135.
- Damians, I.P., Bathurst, R.J., Adroguer, E.G., Josa, A., Lloret, A. (2018). Sustainability assessment of earth-retaining wall structures. *Environmental Geotechnics*, 5(4), 231–247.
- Gardoni, M.G., Zornberg, J.G., Palmeira, E.M., Touze, N. (2024). An International Initiative on Geosynthetic Education. *Soils and Rocks*, Vol. 47, No. 2, April, 10 pp.
- Giroud, J.P. (2008). Criteria for Granular and Geotextile Filters. Terzaghi Lecture, Geo-Congress 2008, New Orleans, LA, 11 March. <https://giroud.geoengineer.org/presentations-videos/asce-terzaghi-lecture>
- Giroud, J.P., Bonaparte, R. (1989). Leakage through liners constructed with geomembranes – Part II. Composite liners. *Geotextiles and Geomembranes*, Vol. 8, No. 1, pp. 11-50.
- Koerner, R.B. (2012). Designing with Geosynthetics. Sixth Edition. Volumes 1 and 2.
- Nguyen, T. T. H., Habók, A. (2021). Educational Reforms and Curriculum Transformation in Higher Education: A Comparative Perspective. *Education Sciences*, 11(10), 611. <https://doi.org/10.3390/educsci11100611>
- Pantazidou, M. (2023). Personal communication, Athens, Greece, 05 October.
- Touze, N. (2021). Healing the World: A Geosynthetics Solution. *Geosynthetics International*, Vol. 28, No. 1, January, pp. 1-28.
- United Nations (2015). Transforming our world: the 2030 Agenda for Sustainable Development. United Nations General Assembly. <https://sdgs.un.org/2030agenda>
- Zornberg, J.G. (2012). Ingenuity in Geotechnical Design using Geosynthetics. *Geotechnical Engineering State of the Art and Practice*, Geotechnical Special Publication no. 226, ASCE, State-of-the-Art lecture at the Geo-Congress 2012, Oakland, California, March, pp. 398-419.
- Zornberg, J.G. (2013). The International Geosynthetics Society (IGS): No Borders for the Good Use of Geosynthetics. 25-Year Retrospectives on the Geosynthetic Industry and Glimpses into the Future, Twenty-fifth Geosynthetic Research Institute Conference (GRI-25), April 01-02, Long Beach, California, pp. 342-357.
- Zornberg, J.G. (2017). Geosynthetics in Roadway Infrastructure. *Procedia Engineering*, Elsevier, Transportation Geotechnics and Geoecology, May, Vol. 189, pp. 298-306.
- Zornberg, J.G., Touze, N., Palmeira, E.M. (2020). Educate the Educators: An International Initiative on Geosynthetics Education. Proceedings of the International Conference on Geotechnical Engineering Education, GEE2020, June 24-25, Athens, Greece, 10p.
- Zornberg, J.G. (2021). Introduction to Geosynthetics. Educate the Educators Program. International Geosynthetics Society (IGS). Available at: <https://www.geosyntheticssociety.org/ete-introduction-geosynthetics-students/>
- Zornberg, J.G., Subramanian, S., Roodi, G.H., Yalcin, Y., Kumar, V.V. (2024). Sustainability Benefits of Adopting Geosynthetics in Roadway Design. *International Journal of Geosynthetics and Ground Engineering*, Springer, Vol. 10, May, 27 pp.

Author's Bio

Jorge G. Zornberg, The University of Texas at Austin (USA)

Dr. Jorge G. Zornberg has over 35 years of experience in the practice and research of geotechnical and geosynthetic engineering. His research focuses on transportation geotechnics, environmental geotechnics, geosynthetic, unsaturated soils, and expansive clays. As an engineering consultant, he has served as an expert witness in litigation and forensic geotechnical cases. From 2010 to 2014, he was President of the International Geosynthetic Society (IGS). He has authored over 550 technical publications, contributed to several book chapters, and holds three patents. Prof. Zornberg has received numerous prestigious honors, including the Ralph B. Peck Award, Croes Medal, and Collingwood Prize from ASCE; the Mercer Lecture Award from ISSMGE and IGS; and the IGS Service Award, IGS Award, and Young IGS Member Award. He was also the recipient of the Presidential Early Career Award for Scientists and Engineers (PECASE) from President George W. Bush. In 2019, the IGS established the "Zornberg Lecture," an honorary lecture recognizing his outstanding contributions to the geosynthetic discipline.

***Curricula: Undergraduate,
(Post)Graduate,
Doctoral***

Game development-based learning curriculum module for undergraduate soil mechanics/geotechnical engineering classes

B. Ajmera, C. Rutherford, A. Poplin, A. Emery, J. Sabrowsky & P. Chung

Iowa State University, Ames, IA, United States

bajmera@iastate.edu, cassier@iastate.edu, apoplin@iastate.edu, aemery@iastate.edu,
jws@iastate.edu, & chung@iastate.edu

ABSTRACT: Game development-based learning (GDBL) has been shown to promote student ownership in the learning process; critical thinking and logical reasoning; creativity in a more inclusive learning environment; leadership, teamwork and communication skills. This paper describes a new active learning GDBL curriculum that was developed to improve students' knowledge of geotechnical principles, professional skills, and attitudes. The module designed for the laboratory portion of an undergraduate soil mechanics/geotechnical engineering course consists of various activities over the course of the semester. It includes eleven video lectures with a series of worksheets for group activities that lead students through the process of creating their own game. They are provided with an opportunity to get constructive feedback through a community game-night. This feedback is incorporated into the final game that they present and play at the end of the semester. Assessment results indicated that this curriculum module was successful in developing communication and goal-setting skills. Additionally, students noted that they enjoyed the fun aspects associated with the GDBL curriculum module in an otherwise very technical course. Finally, although this curriculum module was implemented in the soil mechanics laboratory, it can be adopted to any class at any institution.

Keywords: *Game development-based learning, Soil mechanics/geotechnical engineering, Professional skills, Teamwork, Communication*

1 Introduction

The COVID-19 global pandemic significantly disrupted traditional teaching and learning methods promoting a rapid shift to online and hybrid learning environments. While these adaptations ensured instructional continuity, research indicates that they negatively impacted student engagement, learning outcomes, teamwork dynamics and the development of essential professional skills (Wu & Teets, 2021; Marinoni et al., 2020; Zamborová et al., 2021; Kamysbayeva et al., 2021). Although in-person classes have resumed, classroom attendance and engagement has not returned to pre-pandemic levels highlighting the need for innovative pedagogical approaches that actively involve students in their learning process (Williams, 2022; Almendingen et al., 2021).

Game development-based learning (GDBL) presents a promising strategy for fostering student engagement, enhancing creativity, and strengthening both technical and professional competencies. Prior studies have demonstrated the potential of game-based learning (GBL), in which gaming elements are incorporated in the classroom, to improve cognitive skills, motivation and social interactions (Aldrich, 2004, 2009; Egenfeldt-Nielsen, 2007; Gee, 2003). Most of GBL research has focused on students playing games rather than designing them, with particular emphasis on software-based game development in computer science education (Comber et al., 2019; Opalli & Cagiltay, 2018). The constructivist learning theory suggests that students benefit more from actively creating educational tools, such as games, than from passive participation (Baytak et al., 2011; Marlow, 2012; Pertelín-Ricárdez & Sacristán, 2015). This approach promotes deeper understanding, critical thinking, and teamwork skills.

Gaming in the classroom has been shown to increase retention, motivation and cognitive abilities while providing an opportunity to experiment and develop a deeper understanding of course material (Lawrence et al., 1975; Krause et al., 2015; Koster, 2013; Juul, 2013; Gentile & Gentile, 2021; Tang & Chang, 2013). Granic et al. (2014) categorized the benefits of playing games into cognitive, motivational, emotional and social engagement components. Increased cognitive skills include faster and more accurate attention allocation, higher spatial resolution in visual processing, and enhanced mental rotation abilities (Uttal et al., 2013; Green & Bavelier, 2012). Games may also provide immediate feedback reinforcing student persistence and achievement (Dweck & Molden, 2005; Sweetser & Wyeth, 2005).

Despite the well-documented advantages of GDBL, there remains a gap in its application to non-computer science disciplines such as civil and geotechnical engineering. Addressing this gap, this study introduces a novel GDBL curriculum module specifically designed for undergraduate soil mechanics/geotechnical engineering courses. The curriculum integrates active learning strategies by requiring students to collaborate in teams to design, prototype, and refine educational games (Deshpande & Huang, 2011; Veshosky & Johanne, 1991) centered on core geotechnical engineering concepts.

The goal of the project is to improve the technical knowledge of the students as well as their professional skills and attitudes by engaging them in designing and implementing a game and creating enjoyable learning environment. The research was guided by the following empirical questions:

1. Learning outcomes: Is GDBL associated with an increase in the mastery and application of technical course concepts for the students?
2. Professional skills: What do group members report about the engineering professional skills of themselves and of their teammates over the course of the semester?
3. Motivation and engagement: What do students report about their interest/enjoyment, perceived competence, effort, and value/usefulness of technical content that uses the GDBL?

This paper details the structure and implementation of the GDBL curriculum module in a geotechnical engineering course which includes a series of video lectures, guided worksheets, and a community game-night for iterative feedback. By engaging in game development, students reinforced their technical knowledge while simultaneously developing essential professional skills in communication, teamwork, and leadership. Assessment results are not provided in this paper and are available in Sabrowsky et al. (2024) and Rutherford et al. (2025). These results indicate that this GDBL curriculum can enhance student engagement and professional skill development demonstrating its potential for broader adaption in engineering education and beyond. This research contributes to the ongoing efforts to modernize engineering education through interactive, student-centered learning methodologies. The findings provide valuable insights into the effectiveness of GDBL in fostering deeper learning and increasing student motivation (Sabrowsky et al., 2024; Rutherford et al., 2025), while this paper provides a scalable model that can be adapted across various STEM disciplines.

2 Implementation overview

The GDBL curriculum implemented at Iowa State University (ISU) was structured using the principles of Universal Design for Learning (UDL), a framework that promotes inclusivity by ensuring that students engage with the material through multiple methods. UDL supports diverse learning styles by incorporating choice, collaboration, and self-reflection, while also fostering essential professional skills such as goal-setting and problem-solving. The implementation occurred in the CE 360 (now, CE 3600) - Geotechnical Engineering course, which is the undergraduate introduction course in soil mechanics at ISU. Implementations of the GDBL curriculum occurred in three semesters across five to six sections per semester allowing for the refined curriculum presented in this paper. Across the three semesters, CE 360 was taught by five different instructors including all of the geotechnical engineering faculty at ISU as well as a graduate student who served as the instructor of record during one semester.

Students collaborated in teams to design educational games centered on fundamental geotechnical concepts. Over each of the semesters, teams worked through the process of developing a playable prototype of a serious geotechnical engineering game, which they presented and played at the end of the semester. A serious game is defined as a game that is developed for more than just fun and enjoyment. Rather, it focuses on real-world problems and often includes learning or training. To support the game-design process, instructors provided instructional videos on game design and mechanics,

selection of game types, and the integration of dramatic and formal game elements. The final presentations of their developed game prototypes by the students covered key aspects of the game mechanics, content relevance, and the connection to geotechnical engineering principles. The course concluded with a game-play session during which the students played and evaluated the other games developed by their classmates.

The student team formation process began by encouraging them to explore three geotechnical engineering topics of personal interest broadening their understanding beyond classroom materials. This approach aimed to develop their ability to research and synthesize information independently. Student teams were formed based on common topic interests, while also ensuring diversity and avoiding the isolation of underrepresented students. Additional considerations included work habits, scheduling preferences, and the availability for group meetings. These details were collected through an initial student survey.

The incorporation of the GDBL curriculum into CE 360 did not replace any of the existing technical content. Rather, it was strategically integrated into the available class time. Downtime in laboratory sessions was repurposed for game development activities. For example, any unused time during the experimental work was redirected for team discussions and GDBL activities. Additionally, the unused lab session at the end of the semester was allocated to game testing and refinement. An outline of the various GDBL activities during the sixteen-week semester at ISU is shown in Table 1. At ISU, Week 16 is finals week with no laboratory session. Details of the various activities will be summarized in later sections of this paper.

Table 1. GDBL curriculum activities by week in a typical semester of CE 360 at ISU

Week	Activities
1	Demographic survey; Activity 1.1 (video): Games that I play; Activity 1.2 (video): Games vs play; Activity 1.3 (video): Motivation for playing games; Activity 1.4 (video): Types of games
2	Group work on game design brainstorming, conceptualization, prototyping and testing
3	Team knowledge, skills and ability test questionnaire and learning climate question surveys; Activity 2.1 (video): Formal elements of games; Group work on game design brainstorming, conceptualization, prototyping and testing
4	Activity 2.2 (video): System dynamics; Group work on game design brainstorming, conceptualization, prototyping and testing
5	Activity 2.3 (video): Dramatic elements of games; Activity 2.4 (video): Designing a game; Group work on game design brainstorming, conceptualization, prototyping and testing
6	Group work on game design brainstorming, conceptualization, prototyping, and testing
7	Team knowledge, skills and ability test questionnaire survey; Group work on game design brainstorming, conceptualization, prototyping and testing
8	Group work on prototyping and designing a questionnaire for testing
9	Group work on prototyping and designing a questionnaire for testing
10	Group work on prototyping and designing a questionnaire for testing
11	Group work on prototyping and designing a questionnaire for testing
12	Group work on prototyping and designing a questionnaire for testing
13	Testing and playing games
14	Intrinsic motivation inventory survey; Testing and playing games
15	Team knowledge, skills and ability test questionnaire survey; Group reflections; Games due; Game play and testing results presentation

Students developed physical geotechnical engineering game prototypes, iterating the received feedback in their designs. The iterative game design process followed the spiral model in Boehm (1986, 1988), which emphasizes continuous improvement through cycles of prototyping, testing and modification. Initial prototypes were tested within teams before being evaluated by classmates. At least one iteration was required, though many teams opted for additional refinements to enhance gameplay and educational effectiveness. Through this iterative, hands-on process, students reinforced their understanding of geotechnical concepts while simultaneously strengthening teamwork, communication, and critical thinking skills. From the implementation of GDBL curriculum into the course, it was clear that

the course fostered an engaging and interactive learning environment that encouraged creativity and active participation.

Pilot testing of the curriculum allowed challenges during implementation to be addressed in subsequent semesters. For example, during the pilot semester, groups did not begin working on games in earnest until shortly before the due date, despite engaging with the GDBL curriculum from the start of the semester. As such, instructors increased the messaging about the project early in the semester to promote progress. Additionally, the majority of groups during the pilot semester created Jeopardy-style trivia games, which test knowledge of course content among the players, but do not teach course content to game players as intended by the proposed GDBL curriculum. In subsequent semesters, students were provided with more examples of other types of games, which increased the variation of game types.

3 Video lectures and activity worksheets

Towards the beginning of the semester, the students watched a series of video lectures that better prepared them to actively participate in the game-development process. Table 2 provides the titles of the each of the eleven videos that the students watched along with the associated durations. They were asked to watch these videos individually as part of their pre-laboratory assignment. As seen from Table 2, the videos ranged in length from about 8 min to 25 min. On average, they were about 14 min in length. These videos provided the necessary background for the students to complete the associated activity worksheets as a group during the laboratory session. These worksheets were added to the GDBL curriculum after the first semester of implementation as a way to facilitate groupwork and team conversations around the contents of the videos.

Table 2. Pre-laboratory video lecture and duration

Video	Title	Duration
1	Introduction	9 min 56 sec
2	Play vs game definitions	15 min 51 sec
3	Types of games Part 1	7 min 38 sec
4	Types of games Part 2	14 min 41 sec
5	Formal elements of games Part 1	24 min 42 sec
6	Formal elements of games Part 2	14 min 37 sec
7	Dramatic elements of games	11 min 42 sec
8	Prototyping Part 1	15 min 39 sec
9	Prototyping Part 2	9 min 24 sec
10	Activity diagram	18 min 6 sec
11	Iterations and prototyping	9 min 30 sec

After watching the first video, the students completed a worksheet in class that contained three questions: (1) What are some games that you play? List at least three games for each team member; (2) Why do you like these games? Discuss among your team and list at least five reasons; and (3) What are your favorite and least favorite aspects/parts of a game? Discuss among your team and list at least five reasons. The goal of this activity was to initiate conversations among the team members about the games they play, what they enjoy and what they do not in order to start the brainstorming process about the type of game that they would like to develop as it relates to a geotechnical engineering concept.

The second worksheet was associated with the second video (Table 2). In this worksheet, students were asked to think about the differences between a game and play. This worksheet had the following three prompts: (1) How do you define “play?” What are some characteristics of play? What is the opposite of play?; (2) What are “games?” What are the characteristics of a game?; and (3) What are the differences between “playing” and “gaming?”

The class had two video lectures associated with the different types of games. The third worksheet was assigned as part of the group work after the fourth video was assigned in the pre-laboratory preparation

lectures. The worksheet required students to think about the different games that they were familiar with and to begin classifying them into different types. Specifically, the teams were asked to name at least one game for each of the types of games listed. This list included: (1) digital vs. non-digital, (2) single player vs. multiplayer, and (3) competitive vs. cooperative.

Students completed the fourth worksheet after watching the two video lectures associated with the formal elements of games. The prompt for this worksheet asked students to work together to identify the formal elements of two of their favorite games. In particular, they were requested to focus on the following formal elements: (1) Players (number, type, who are they, audience, age range, education level, etc.), (2) Player's interaction with the game (single player vs. game, multiple players vs. game, competitive against players, cooperative, team competition, etc.), (3) Player roles, (4) Player's play style (achievers, explorers, socializers and killers), and (5) Objectives that players try to accomplish within the rules of the game.

The first four worksheets focused on introducing students to the various components associated with game development and to start thinking about how the materials about game design they studied can be applied to the games that they are familiar with. In the fifth worksheet, students begin to implement these components towards the game that they will be developing for the GDBL curriculum assignment. Specifically, the fifth worksheet was related to the brainstorming sessions that help the teams quickly decide on the important aspects of the game. The prompt for this worksheet asked students to sketch a mind-map of their game prototype including its formal elements. They were required to include the following formal elements in the mind-map:

- Players: Who, number of players, roles, play style, and interaction patterns;
- Rules: Define objects, concepts, restricting actions and determining effects;
- Objectives: Capture, chase, race, alignment, rescue or escape, forbidden act, construction, exploration, solution and/or outwit;
- Resources: Lives, units, health, currency, actions, power-ups, inventory, special terrain, and/or time;
- Conflict: Obstacles, opponents and dilemmas; and
- Boundaries: Physical, conceptual and/or emotional.

Specific details about these formal elements were previously discussed in pre-laboratory videos (Table 2). The brainstorming session and worksheet were aided by the contents presented in the two videos associated with prototyping. This worksheet was accomplished as the in-class group activity after both prototyping videos have been completed.

A new worksheet was added after the second implementation of the GDBL curriculum at ISU to foster greater creativity and highlighted the fact that there are no wrong ideas. This worksheet, the sixth in the curriculum, was focused on reverse brainstorming. First, the team selected one of the six scenarios presented. These scenarios were:

1. How can we design the most cost-effective and stable foundation for the next tallest building in the world in an area that has challenging soil conditions (for example, an expansive clay or in a swamp)?
2. What are some new ways that we can prevent landslides of natural and manmade slopes?
3. How would you design an earthquake-resistant dam?
4. What advancements can be made in the collection and analyses of geotechnical data for site characterization?
5. What can we do as a profession to adapt (or become immune) to the challenges posed by climate change?
6. What new technologies or strategies could make mining (or large-scale excavation projects say under a famous landmark) in challenging geotechnical conditions safe from failure?

This worksheet had four phases. In the first phase, students were given five minutes to brainstorm individual ideas on a sheet of paper. The team then had fifteen minutes to come together to discuss and refine (modify or combine) their ideas to turn them into a list of creative, practical and feasible solutions. During the third phase, students spent five minutes to evaluate the list of refined ideas and choose a few of the best feasible solutions. The last phase was a five-minute report in which the students share their plan with their classmates.

The seventh worksheet was related to prototyping. However, instead of a focus on the game that they were developing for this curriculum, this worksheet concentrated on the design of a questionnaire to measure the learning outcomes of their game during the play sessions. The prompt for this worksheet

read: “One of the goals of designing a geotechnical engineering game is for the players to learn a concept from this class. What are at least five questions that players will answer before and after playing to game? How will you know if they have learned the concept? Are your questions short answer, multiple choice, Likert-scale or other?”

The eighth and final worksheet for the GDBL curriculum was related to describing the game and its rules for the prototyping work undertaken by the team. The students were asked to provide: (1) the name of the game, (2) goal of the game, (3) the premise/story using three to five sentences, (4) players including the number, age range, etc., (5) formal elements of the game, and (6) dramatic elements of the game. In addition, they were given the following directions associated with the description of the rules for the game: “Draft the rules of the game (who starts, how are turns taken, what is the game play, how to win, how does the game end, etc.). You will need to be able to explain how to play your game to someone who has never played it before.”

4 Grading rubrics

The videos in Table 2 were posted to the learning management site at ISU – Canvas – for the students to view prior to coming the associated lab sessions. Each video had a short multiple-choice question at the end of the video that the students were required to answer based on the contents of the video. This question was merely intended as motivation for the students to watch the video to completion. The students had an unlimited number of attempts to answer the question correctly, which gave them points in the class participation category for the course syllabus.

Worksheets were collected at the end of each associated lab session but were not graded. The intent of the worksheets was to facilitate groupwork and prompt them to think collectively about various aspects of the game-development project. These worksheets were added after the first (pilot) implementation of the GDBL curriculum in CE 360, after the instructors observed that students waited until the last minute to begin prototyping their game with very little team interaction about the videos until that point.

Students were asked to ensure that their final presentations included the following: (1) name of the game, (2) goal of the game, (3) premise/story, (4) players, (5) formal elements of the game, (6) dramatic elements of the game, (7) details of how they made changes to the first prototype after either the community game play session or the team game play prior to the final submission, (8) instructions on how to play the game, and (9) an explanation of how their game would contribute to a building a more diverse engineering workforce while creating a more equitable and inclusive environment. Final presentations were graded by the instructor of the CE 360 course in which the GDBL curriculum was implemented. No special rubrics or guidelines were provided to the instructors to complete the grading of the final presentations.

5 Example games developed at ISU

The games developed by the CE 360 students in the implementations at ISU varied substantially. Some of the games had very playful elements with very little technical content. On the opposite end of the spectrum, some of the games focused heavily on the technical content with little elements of playfulness. The following is a brief list of example games (in no particular order) that were developed to demonstrate the spectrum of game prototypes created.

- Variations of Jeopardy in which students selected four to six different categories associated with modules in the CE 360 course with four to six questions of increasing difficulty in each category.
- Variations of Jenga in which questions were added to the blocks that the players must answer correct to score points with the winner having the greatest number of points when the tower falls.
- Variations of Twister in which the player must answer a question correctly or be penalized by placing or moving a limb to the color associated with their turn.
- Variations of Candyland in which the players must reach the end of the board by advancing through the answering of correct questions.
- Variations of Heads Up in which the one player guesses as many terms as possible from cards visible to the other player who provides clues to the guesser.

- Variations of Beer Pong in which cups on the opposite end of the table are eliminated when the person tossing the ping pong ball answers the associated question correctly.

The spectrum of games covered contents from all of the modules that were associated with the CE 360 class at ISU. This list of topics included: (1) the historical perspective of geotechnical engineering, (2) rock cycle, (3) particle size distributions, (4) soil consistency, (5) engineering classification, (6) subsoil exploration, (7) weight-volume relationships, (8) compaction, (9) permeability and seepage, (10) in-situ stresses, (11) compressibility, (12) shear strength, (13) lateral earth pressures, (14) slope stability, (15) bearing capacity, and (16) geosynthetics.

6 Outcomes from implementation in CE 360 at ISU

The main results from survey and learning outcomes from the implementations of the GDBL curriculum in CE 360 at ISU are available in Sabrowsky et al. (2024) and Rutherford et al. (2025). The main focus of this paper is on presenting the key elements of the curriculum and its implementation in the course. However, some of the major outcomes are presented here to provide context towards the benefits of the incorporation of the GDBL curriculum for the students involved.

An increase in the effort that the students perceived by adding the GDBL activities to the curriculum were found to correspond to an increase in their communication ($t(48) = 2.462$, $p = 0.02$) and problem-solving skills ($t(48) = 2.404$, $p = 0.02$; as reported in Rutherford et al., 2025). Interestingly, there were no statistically significant reported increases in the enjoyment among the students in the tasks that they were assigned. Conflict resolution among the students was found to be related to increased valuing of the GDBL activities ($t(48) = 3.513$, $p < .01$, as reported in Rutherford et al., 2025). Conflict resolution was not found to have a statistically significant relationship with enjoyment of the task. Similarly, neither time-management abilities nor goal-setting skills predicted students' enjoyment of the GDBL activities, but both were statistically significant predictors of other dimensions of motivation, including reported effort ($t(48) = 2.661$, $p = 0.01$) and reported valuing of the activities ($t(48) = 2.146$, $p = 0.04$), as presented in Rutherford et al. (2025).

Descriptive analysis of interviews conducted with a convenience sample of participants ($N = 17$ volunteers) added insight to these results. When asked why they believed their instructors assigned the GDBL project, all students indicated a belief that the project was intended to improve teamwork skills, which they agreed were integral to careers in engineering. No participant suggested that the project was designed to promote deep learning of the course concepts through active learning. When asked to describe how their teams worked together and what each teammate contributed to the final project, nearly all participants' descriptions of their team dynamics focused on interpersonal skills like organization (e.g., acquiring materials), goal-setting (keeping the project on-track), time management (making productive use of team work time), and conflict resolution (e.g., bringing the team to a consensus regarding the game design) rather than knowledge of course concepts.

7 Limitations from prior implementations

While the GDBL curriculum implemented in CE 360 at ISU demonstrated promising outcomes in student engagement and learning, several limitations should be acknowledged. First, the study was conducted within a single institution, limiting the generalizability of the findings to other universities with different student demographics, institutional structures, or instructional approaches. The curriculum was implemented across three semesters with five different instructors in multiple sections, allowing for iterative refinements. However, the lack of cross-institutional validation presents a constraint on assessing the broader applicability of the GDBL curriculum.

The integration of the GDBL curriculum in CE 360 relied on repurposing available laboratory time to ensure that none of the existing technical content was replaced. While this approach warranted that essential course material remained intact, it also constrained the amount of time students could dedicate to the game development. Thus, the effectiveness of the curriculum may vary in courses where laboratory downtime is minimal or where additional instructional time is not available.

Another limitation relates to the team formation and group dynamics. Although efforts were made to ensure diversity in team composition and to align students based on shared interests in geotechnical engineering topics, scheduling preferences, and work habits, disparities in effort and engagement levels within teams may have affected learning outcomes. Unequal contributions by the team members may influence the overall experience, potentially impacting the development of both technical and professional skills from the GDBL curriculum.

At ISU, CE 360 is typically the first introduction to geotechnical engineering and soil mechanics concepts for the students. Thus, they are still learning about the various aspects of field. In addition, while students were provided with instructional videos and structured guidance on game design, they undoubtedly had varying levels of familiarity with game mechanics. Learning of both soil mechanics and game mechanics may have affected the quality and complexity of the developed prototypes. Some students may have struggled with the effective integration of geotechnical engineering concepts into their game designs. Finally, the time provided to the students to develop their games was limited to the time available in laboratory sessions after they completed the traditional geotechnical engineering experiments in CE 350. As a result, students may not have had sufficient time to brainstorm alternative game mechanics. This could influence the depth of learning that could be achieved through the GDBL curriculum.

Despite the limitations discussed above, the GDBL curriculum demonstrated its potential as an innovative pedagogical tool for geotechnical engineering education. Addressing these constraints in future implementations – such as expanding the study to multiple institutions and optimizing team dynamics – could further enhance its effectiveness and scalability.

8 Concluding remarks

The implementation of the GDBL curriculum in CE 360 at ISU demonstrated the potential of game development-based learning to enhance student engagement, foster teamwork, and reinforce technical competencies in geotechnical engineering education. By actively participating in the game development process, students not only gained a deeper understanding of geotechnical concepts but also developed essential professional skills such as communication, problem-solving, and conflict resolution. These findings align with prior research suggesting that constructivist learning approaches, particularly those that encourage active student involvement, contribute to improved learning outcomes and motivation.

Despite the promising results, several limitations must be acknowledged. The study was conducted at a single institution, limiting the generalizability of the findings. Additionally, while the integration of GDBL into the curriculum was carefully designed to avoid displacing core technical content, the approach relied on repurposing laboratory downtime to the game development, which may not be feasible in all educational settings. Furthermore, while students reported increased effort and motivation in the game development process, no statistically significant improvement in their enjoyment of the tasks was observed. Future research should explore strategies to enhance student enjoyment while maintaining the educational rigor of the curriculum.

Future studies should explore the implementation of GDBL curriculum in diverse institutional settings to access its generalizability and scalability. Research is also needed to evaluate the impact of different team formation strategies and the associated impacts on collaboration, engagement, enjoyment and learning outcomes. Longitudinal research to evaluate the retention of technical content and professional skill development over time may also be valuable.

In conclusion, this study provides a scalable and innovative pedagogical model that can be adapted beyond geotechnical engineering to enhance student engagement and learning outcomes across STEM education. By leveraging the principles of active learning and game design, GDBL represents a promising avenue for modernizing engineering education and fostering deeper student involvement in the learning process.

Acknowledgements

This project/material is based upon work supported by the Iowa Space Grant Consortium under NASA Award No. 80NSSC20M0107, the Iowa State University Office of the Vice President for Research under the Game2Work Presidential Interdisciplinary Research Initiative (PIRI), the United States Universities

Council on Geotechnical Education and Research (USUCGER), and the Iowa State University Center for Excellence in Learning and Teaching (CELT).

References

- Aldrich, C. (2004). *Simulations and the Future of Learning: An Innovative (And Perhaps Revolutionary) Approach to E-Learning*. Pfeiffer.
- Aldrich, C. (2009). *The Complete Guide to Simulations and Serious Games: How the Most Valuable Content will be Created in the Age beyond Gutenberg to Google.* Pfeiffer.
- Almendingen, K., Sandsmark Morseth, M., Gjølstad, E., Brevik, A., Tørris, C. (2021). Student's Experience with Online Teaching Following COVID-19 Lockdown: A Mixed Methods Explorative Study. *PLoS ONE*, 16(8), e0250376.
- Boehm, B. (1986). A Spiral Model of Software Development and Enhancement. *ACM SIGSOFT Software Engineering Notes*, 11(4), pp. 14-24.
- Boehm, B. (1988). A Spiral Model of Software Development and Enhancement. *IEEE Computer*, 21(5), pp. 61-72.
- Comber, O., Motschnig, R., Mayer, H., Haselberger, D. (2019). Engaging Students in Computer Science Education through Game Development with Unity. *2019 IEEE Global Education Engineering Conference (EDUCON)*, pp. 109-205.
- Deshpande, A. A., Huang, S. H. (2011). Simulation Games in Engineering Education: A State-of-the-Art Review. *Computer Applications in Engineering Education*, 19(3), pp. 399-410.
- Dweck, C. S., Molden, D. C. (2005). Self-Theories: Their Impact on Competence, Motivation and Acquisition. In *Handbook of Competence and Motivation*, pp. 122-140.
- Egenfeldt-Nielsen, S. (2007). *Beyond Edutainment: The Educational Potential of Computer Games*. Continuum Press.
- Gee, J. P. (2003). *What Video Games Have to Teach Us About Learning and Literacy*. Palgrave MacMillan.
- Gentile, D. A., Gentile, J. R. (2021). *Learning from Video Games (And Everything Else)*. Cambridge University Press.
- Green, C. S., Bavelier, D. (2012). Learning, Attentional Control, and Action Video Games. *Current Biology*, 22.
- Juul, J. (2013). *The Art of Failure: An Essay on the Pain of Playing Video Games*. The MIT Press.
- Kamysbayeva, A., Koryakov, A., Garnova, N., Glushkov, S. Kilmenkova, S. (2021). E-Learning Challenge Studying the COVID-19 Pandemic. *International Journal on Educational Management*. 35(7), pp. 1492-1503.
- Koster, R. (2013). *A Theory of Fun for Game Design*. Parahlyph Press, Inc.
- Krause, M., Mogalle, M., Pohl, H., Williams, J. J. (2015). A Playful Game Changer: Fostering Student Retention in Online Education with Social Gamification. *Proceedings of the Second ACM Conference on Learning @ Scale*, pp. 95-102.
- Lucas, L. A., Postma, C. H., Thompson, J. C. (1975). A Comparative Study of Cognitive Retention using Simulation-Gaming as Opposed to Lecture-Discussion Technique. *Journal of Education, Issues and Trends in American Education*, 52(4), pp. 261-266.
- Marinoni, G., van't Land, H., Jensen, T. (2020). The Impact of COVID-19 on Higher Education Around the World. *IAU Global Survey Report*. International Association of Universities.
- Rutherford, C., Ajmera, B., Poplin, A., Emery, A., Sabrowsky, J., Chung, P. (2025). Impact of Game-Design Based Learning on Student Engagement, Achievement, and Motivation in Undergraduate Geotechnical Engineering Classes. *Geotechnical Special Publication*, 367, pp. 69-78. <https://dr.lib.iastate.edu/bitstreams/544d6d66-5ed6-44c3-9f71-79f05fa36608/download>
- Sabrowsky, J., Ajmera, B., Rutherford, C., Poplin, A., Emery, A. (2024). Improving Student Engagement, Achievement and Motivation using Game-Design Based Learning in Undergraduate Geotechnical Engineering Classes. *Geotechnical Special Publication*, 353, pp. 377-385. <https://dr.lib.iastate.edu/entities/publication/dda0b1fc-e658-42c4-ae42-dad991e827ce>
- Sweetser, P., P. Wyeth, P. (2005). GameFlow: A Model for Evaluating Player Environment in Games. *Computers in Entertainment*, 3, Article 3A.

- Topalli, D., Cagiltay, N. E. (2018). Improving Programming Skills in Engineering Education through Problem-Based Game Projects with Scratch. *Computers and Education*, 120, pp. 64-74.
- Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., Newcombe, N. S. (2013). The Malleability of Spatial Skills: A Meta-Analysis of Training Studies. *Psychological Bulletin*, 139, pp. 352-402.
- Veshosky, D., Johannes, H. E. (1991). Civil Engineering Project Management Game: Teaching with Simulation. *Journal of Professional Issues in Engineering Education and Practice*, 117(3), pp. 203-213.
- Williams, T. (2022). Class Attendance Plummets Post-COVID. *The Times Higher Education*.
- Wu, F., Teets, T. S. (2021). Effects of the COVID-19 Pandemic on Student Engagement in a General Chemistry Course. *Journal of Chemical Education*, 98 (12), pp. 3633-3642.
- Yang, Y. C., Chang, C. L. (2013). Empowering Students Through Digital Game Authorship: Enhancing Concentration, Critical Thinking, and Academic Achievement. *Computers and Education*, 68, pp. 334-344.
- Zamoroyvá K., Stefanutti, I., Kilmová, B. (2021). CercleS Survey: Impact of COVID-19 Pandemic on Foreign Language Education in Higher Education. *CercleS*, 11(2), pp. 269-283.

Authors' bios

Beena Ajmera, Iowa State University (United States)

Dr. Beena Ajmera is an Assistant Professor in the Department of Civil, Construction and Environmental Engineering. She earned her doctorate in Civil Engineering with focus in Geotechnical Engineering from Virginia Polytechnic Institute and State University and her MS in Civil Engineering with emphasis in Geotechnical Engineering, BS in Civil Engineering and BA in Applied Mathematics from California State University. She has conducted research related to geotechnical engineering and has taught over two dozen courses in civil engineering. She has supervised over 130 high school to graduate students and middle and high school teachers on various research projects. She served as PI of National Science Foundation Research Experiences for Teachers grant and published over 60 products in engineering education. She is actively involved in various professional societies including serving as Director of the National Geo-Institute Geo-Challenge Student Competitions. She is registered as a Professional Engineer in the State of California.

Cassandra Rutherford, Iowa State University (United States)

Dr. Rutherford is an associate professor in geotechnical engineering at Iowa State University and holds the endowed Richard L. Handy Professorship. A licensed professional engineer in Texas, she teaches courses in advanced soil testing, foundations, and geotechnical engineering. Her research spans geotechnical hazards, renewable energy foundations, and engineering education, including the development of women engineering students' identities, engineering ethics, and project-based learning. She received an NSF CAREER award for experimental modeling of tidal current turbine foundations and has led national and international projects on soil behavior under dynamic loading. Committed to K-12 and public outreach, she has developed STEM programs for students from elementary to high school. She actively contributes to professional committees, including the Geo-Institute and the Deep Foundations Institute. Passionate about bridging research and education, Dr. Rutherford integrates hands-on learning experiences to prepare future engineers for the challenges of sustainability, infrastructure resilience, and ethical decision-making.

Alenka Poplin, Iowa State University (United States)

Dr. Alenka Poplin is an Associate Professor of Geoinformation Science in the Community and Regional Planning Department. She holds a PhD in geoinformation science from Vienna University of Technology, Master of Business Administration from Clemson University and Master of Surveying from the University of Ljubljana. She is also the director of the Geogames Lab and an editor and co-editor of the special issue journals in *Environment and Planning B: Urban Analytics and Citizen Science*, *Sustainability* and

Urban Planning. Her research interests include serious online geogames and games for change, online geogames for civic engagement, smart and sustainable cities, emotions related to places, mapping emotions in a geographic information system. She is actively involved in several projects including “Caretaker buddy” that focuses on creating a mobile gamified application for caregivers of patients with Parkinson disease and several projects that study learning and motivation by creating games in geotechnical engineering education.

Alyssa Emery, Iowa State University (United States)

Dr. Alyssa Emery is an Assistant Professor of learning sciences in the School of Education. Broadly speaking, her research focuses on achievement motivation, with a particular emphasis on the experiences of students with disabilities in general education and college classrooms. Additionally, she is interested in innovative social science methodologies. Before earning her Ph.D., Dr. Emery was a special education teacher in Tulsa, Oklahoma. At Iowa State, she supports the teacher preparation program by teaching Educational Psychology (EDUC 3320/EDUC 3330), and graduate programming by offering a variety of courses in theories of learning, motivation, and disability studies, as well as the qualitative methods sequence. Dr. Emery holds a PhD in Educational Studies (Educational Psychology) and a MA in Educational Studies (Educational Psychology) from The Ohio State University and a BA in Philosophy and English from William Jewell College.

Justin Sabrowsky, Iowa State University (United States)

Dr. Justin Sabrowsky is a former graduate student in the School of Education at Iowa State University. He is currently a Lecturer in the Department of Mathematical Sciences at Appalachian State University Hickory Campus. Dr. Sabrowsky holds a BS and BA from the University of Minnesota – Duluth and a MS and PhD from Iowa State University.

Paul Chung, Iowa State University (United States)

Mr. Paul Chung is a graduate research assistant in the Research Institute for Studies in Education at Iowa State University. His research interests are in the psychological well-being of virtual team collaboration in the digital spaces and the application of self-determination theory to technology design. Mr. Chung holds a BA in Business Management from the University of Iowa and a MEd in Curriculum and Instructional Technology from Iowa State University.

GEOMME project: an experience-based approach to teaching sustainable landslide hazard mitigation

V. Capobianco¹, G. Gilbert¹, L. Piciullo^{1,2}, T.H. Kwon³, R. Nishii⁴, N. Watanabe⁴, J.Y. Park⁵, M. Uzielli⁶

¹*Department of Natural Hazards, Norwegian Geotechnical Institute (NGI), Oslo, Norway*
vittoria.capobianco@ngi.no, graham.gilbert@ngi.no, luca.piciullo@ngi.no

²*Department of Civil and Energy Engineering, Oslo Metropolitan University (OsloMet), Oslo, Norway*

³*Department of Civil and Environmental Engineering, Korean Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea*
t.kwon@kaist.ac.kr

⁴*Research Institute for Natural Hazards and Disaster Recovery, Niigata University, Niigata, Japan*
ryo-nishii@gs.niigata-u.ac.jp; jibanken@cc.niigata-u.ac.jp

⁵*Geologic Environment Division, Korea Institute of Geoscience and Mineral Resources (KIGAM), Daejeon, South Korea*
jypark@kigam.re.kr

⁶*Department of Civil and Environmental Engineering, University of Florence, Florence, Italy*
marco.uzielli@unifi.it

ABSTRACT: In the pursuit of achieving climate neutrality within one generation, the geotechnical and geoscientific community are focusing increasingly on developing and implementing sustainable alternatives to traditional engineering measures for landslide risk reduction. For instance, vegetation and its parts are a Nature-based Solution (NbS) for climate change adaptation, offering also benefits for climate mitigation and biodiversity improvement. This shift in paradigm calls for traditional geoscientific fields, such as geotechnical engineering, engineering geology, and soil mechanics to incorporate in their agendas discussions and initiatives aimed at defining how to account for the hydro-mechanical effects of vegetation in unsaturated soils, particularly for improving slope stability and mitigating shallow landslide hazards. Intensive, research-based courses support this transition by offering focused lectures on emerging geotechnical topics related to such aspects, helping postgraduate students in remaining updated, enhancing their skills, and advancing personally and professionally. This paper presents the research- and experience-based courses in the GEOMME partnership project, with a particular focus on the courses on rainfall-induced landslides developed in 2024 and 2025. The paper outlines the courses' modules including practical exercises, case studies, and relevant references. This contribution aims to present a model for integrating recent advancements in landslide detection, prediction, and mitigation into future curricula, with a specific focus on quantifying, modelling, and monitoring the hydro-mechanical effects of vegetation in unsaturated soils to improve slope stability.

Keywords: *International course, Rainfall-induced landslides, Case studies, Soil bioengineering, Slope stability*

1 Introduction

The GEOMME international partnership for climate-induced geohazard mitigation, management, and education in Japan, South Korea, and Norway, is committed to advancing excellence in education and research to increase societal resilience against climate-induced geohazards, such as landslides and debris flows among others. The project started in 2021 and has a 5-year duration. The peculiarities of the GEOMME course format lie in its focus on experiential learning and in the cross-disciplinary exchange of geohazard education between the participant institutions from the three countries involved. The course structure typically consists of one week of combined in-class lectures and practical exercises, followed by a second week of field excursions.

The paper begins by introducing the organizing institutions and outlining the four key areas of scientific advancement. It then provides a detailed description of the learning objectives, structure, and content of the 2024 and 2025 courses. Finally, the paper concludes with a discussion and key takeaways from this experience and possible integration of this model in future curricula.

1.1 The organizing institutions

The project has 7 partners representing research institutes, universities, and municipalities in South Korea, Japan, and Norway. Each country is represented by both a university and a research institute. Norway's partners include the Norwegian Geotechnical Institute (NGI), which also coordinates the project, and the University of Tromsø. South Korea is represented by the Korea Advanced Institute of Science and Technology (KAIST) and the Korea Institute of Geoscience and Mineral Resources (KIGAM), while Japan is represented by the National Research Institute for Earth Science and Disaster Resilience (NIED) and Niigata University.

1.2 Other supporting universities and organizations

In addition to the core partners, universities and research institutes specializing in geotechnics, forestry, natural hazards, and environmental protection have supported GEOMME by contributing to the course planning, hosting workshops and field visits. In 2024, Gangneung Wonju National University facilitated a visit to its real-scale debris flow facility and a workshop, and the National Institute of Forest Science (NIFoS) introduced the National Landslide Information System. In 2025, the University of Florence has been instrumental in organizing the course and excursions in Italy. The 2025 workshop will be held at the Italian Institute for Environmental Protection and Research (ISPRA) in Rome, with participation from the Italian Civil Protection.

1.3 Progress domains and past editions

The activities in the GEOMME partnership gravitate around four areas for collective scientific advancement, termed 'progression domains' (PD). These are the thematic areas of collaboration, identified based on the perceived knowledge gaps in research and education.

An overview of the four PDs is shown in **Figure 29**. PD1 provides a general introduction to the natural hazards and risks in a changing climate, with an emphasis on landslides, rockfalls and snow avalanches. The focus of PD2 is on large-scale modelling of both release and propagation, especially of snow avalanches. PD3 focuses on detection, prediction, and mitigation of landslides and debris flows applying advanced technologies. PD4 addresses sustainable approaches for landslide risk reduction and soil improvement.

2 Structure of the courses on landslide hazard

The aim of this paper is to provide an insight on the topics included in the courses organized within the PD3 and PD4 in 2024 and 2025. Both courses focus on landslide hazard, slope stability, modelling, monitoring and mitigation. The 2025 course has not yet been held at the time of writing. Therefore, all contents outlined herein may be subject to changes.

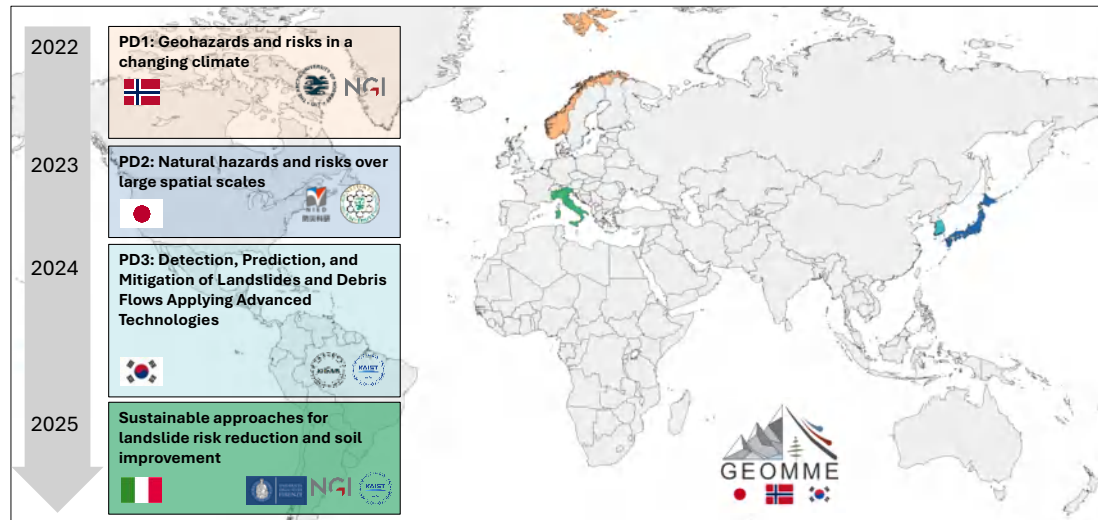


Figure 29. Progress domains and relative year, hosting country and institutes responsible for the course organization

2.1 Learning objectives

Each year, the course defines four main learning objectives, which reflect the experience-based type of learning of GEOMME. In 2024, the main objectives were: understand the physics of landslide and debris flow mechanisms including predisposing and triggering factors; gain practical skills on advanced techniques and machine learning for landslide susceptibility mapping and hazard assessment; learn the principles, applications, and the technical and social components of landslide early warning; select and design active and passive landslide and debris flows risk mitigation options.

The learning objectives for the 2025 course are: understand the effects of climate change on landslide hazards and develop climate-adaptive mitigation strategies; learn about laboratory, field testing and monitoring of hydro-mechanical reinforcement by roots for slope stability; learn to simulate and analyse the effects of root systems (at stand or forest scale) on slope stability using basic and advanced modelling techniques; learn conventional and bio-mediated soil reinforcement and improvement.

2.2 Online module

The aim of the online module for the GEOMME course is to provide background and introductory materials to the students. This includes a variety of class materials provided by the lecturers, such as lecture slides/notes, reading materials, relevant references to articles and books and video/pictures. These resources are carefully curated to support the course content and introduce the students to the key topics of the course. To ensure adequate preparation, all materials are made available to students one month prior to the start of the course. The materials are stored on the dedicated GEOMME OneDrive folder, where students can access and review the content at their convenience. Lecturers can also add software that will be used during the exercises, along with detailed instruction on installation and use. Students can contact the instructors or prepare questions to ask during the lecture based on the online materials.

2.3 Course module

The course module includes a one-week on-site program with live lectures for six hours each day, with mornings focused on theoretical learning and afternoons dedicated to practical application using software, tools, coding exercises, or group discussions. The following paragraphs describe the format and relevant references, which may provide reusable ideas for future one-week courses on this topic. The programmes of the past two editions allowed a comprehensive exploration of landslide and debris flow hazards, focusing on both theoretical and practical aspects.

The programme of the 2024 course started with an introduction on physics of landslide initiation and debris flows (**Table 7**). The course then examined large deformation geohazards like debris avalanches and flows, based on the Varnes classification, with real-case examples, including the 2011 Seoul debris

flow (Yune et al., 2017). The physics of debris flows, including equivalent fluid composition, rheology, runout physics, bed entrainment, and impact pressure, were discussed. Following, an introduction to development of structural type-based physical vulnerability curves to debris flow was also provided (Lee et al., 2024). An introduction to the use of GIS allowed the students to gain an insight into the visualisation of data for landslide mapping. Day 2 was dedicated to remote sensing techniques for landslide susceptibility and hazard assessment. Landslide early warning systems and their applications with examples from Europe and Japan were the topic of Day 3. Experiences from implementing a community-based early warning system, encouraging active community participation, were also shared. A role game on landslide early warning decision-making was performed during the practicum. A subsequent practical session was conducted to analyse the regional-scale slope stability across Umyeonsan Mountain during the 2011 Seoul debris flow event. Using theories of infinite slope stability and unsaturated soil mechanics, the factor of safety was calculated for all grid-based slope areas and visualized on a GIS map. An introduction to conventional landslide susceptibility assessment and mapping was provided, along with more recent examples involving the application of Artificial Neural Networks (ANNs) for shallow landslide susceptibility modelling (Lee et al., 2020), which was also the topic of the practicum, with an example from a shallow landslide that occurred in Norway in 2011. The final day was dedicated to landslide risk mitigation, providing a comprehensive overview of both active and passive mitigation measures and more sustainable nature-based solutions (Capobianco et al., 2022). The Landslide Risk Mitigation Toolbox – [LaRiMiT](#) (Uzielli et al., 2017) for the ranking and selection of suitable landslide risk mitigation measures on case-specific basis, was used during the practicum. Students analysed environmental and socio-economic factors, both conceptually as criteria for mitigation measures selection and operationally as inputs to the toolbox. The second topic of Day 5 was a methodology for an optimised debris flow barriers design, based on runout modelling. The code was shared with the students, enabling them to perform an application for a case study, with all input parameters provided by the lecturer.

Table 7. Outline of the programme for the 2024 course in South Korea

DAY 1 Intro to landslide hazard	DAY 2 Remote Sensing	DAY 3 Landslide early warning system (LEWS)	DAY 4 Landslide susceptibility assessment and mapping	DAY 5 Mitigation of landslide and debris flow hazard
Physics of landslide initiation	UAV photogrammetry and hyperspectral imaging	LEWS in Japan	Landslide susceptibility mapping I	Mitigation of Landslide and Debris flows
Vulnerability assessment of landslides	Satellite image collection and analysis	LEWS in Europe	Landslide susceptibility mapping II	Nature-based solutions for landslide hazard mitigation
Physics of debris flows	Satellite based InSAR analysis			Optimized debris barrier design
A case study of the debris flows in 2011 in Umyeon Mountain, Seoul				
Practicum				
Basics of ArcGIS	UAV Photogrammetry and 3D Visualization/Mapping	Landslide early warning decision-making role game or others Distributed factor-of-safety mapping based on infinite slope stability	ANN-based landslide susceptibility model development and its accuracy assessment	The Landslide Risk Mitigation Toolbox for the selection of landslide risk mitigation measures Optimization of debris flow barrier design

The 2025 course program focuses on climate change impacts, adaptation strategies, and innovative solutions for landslide risks and slope stability (Table 2). Day 1 introduces slope stability, including limit equilibrium methods, physics-based models for rainfall-induced shallow landslides, rainfall infiltration modelling, water flow equations, and stress-state approaches for unsaturated soils in determining the Factor of Safety. Following, a general introduction to landslide hazard and risk management in a changing climate is provided, highlighting challenges and opportunities that may arise, such as the use of more sustainable and nature-based solutions (NbS) for hydro-meteorological risk reduction (Capobianco et al., 2025). An introduction to the concept of NbS for climate change adaptation in European and global context are provided. The day includes a practical session using virtual reality to demonstrate NbS for landslide and rockfall hazards, alongside with slope stability exercises. On Day 2, the course dives into the effects of vegetation on slope stability, discussing hydro-mechanical reinforcement from roots, how to quantify them in the laboratory and in field (Giadrossich et al., 2017), and how to parametrize them in slope stability models (DiBiagio et al., 2024). The theory on three stress states approaches in unsaturated soils are now addressed accounting also for the effects of vegetation on the soil shear strength. Following, geotechnical slope stability analysis is conducted using the open access SSAP software <https://www.ssap.eu/> to model the effects of vegetation and other artificial and natural materials for stabilization on the slope stability. Examples from a real case study, which is also visited in the following excursion week are shown during the practicum (Uzielli et al., 2025). Day 3 explores soil bio-engineering, NbS, and ecological engineering for erosion protection and shallow landslide mitigation. The session includes real-case implementation examples from the Horizon 2020 EU project PHUSICOS (Solheim et al., 2021), highlighting key lessons learned and potential barriers to implementation. Day 4 is dedicated to forest management and its role in landslide risk reduction, with specific focus on protection forests from Japan, forest root reinforcement in the Swiss/Italian Alps, and the effects of forest fires on soil properties (Ramirez et al., 2024). The practice session involves using [Slide4Net](#) (Schwarz et al., 2012), a free access tool from EcorisQ that estimates the occurrence probability of a shallow landslide for a given slope with a given forest cover and related root reinforcement. On the final day, the course introduces conventional and bio-based/ bio-inspired solutions for ground improvement, starting from anchors design, nailing, drainage system, to giving some insights of the latest advancements in bio-mediated soil improvement (Ham et al., 2022; Ramos & Kwon, 2023) and root-inspired anchors (Kim et al., 2024).

Table 8. Outline of the programme for the 2025 course in Italy

DAY 1	DAY 2	DAY 3	DAY 4	DAY 5
Climate change impacts and climate change adaptation	Effects of vegetation on slope stability	Soil bioengineering and ecological engineering for slope stability	Protection forests for mitigating landslide risk	Ground improvement: conventional bio-based/inspired solutions
Shallow landslides and slope stability, theoretical background	Hydro-mechanical reinforcement of roots on slope stability: monitoring, testing and modelling	NbS and soil bio-engineering for erosion protection and shallow landslide mitigation	Introduction to forest management, protection forests and the effects on landslide risks – experiences from Japan	Ground improvement, theoretical background (anchors, retaining walls, drainage systems)
Landslide hazard and risk management in a changing climate	Geotechnical modeling of the effects of vegetation on slope stability	Monitoring techniques for NbS effectiveness	From root distribution to protection forest management in the Alps: defining quantitative criteria for guidelines	Design of mechanically stabilized earth wall
Nature-based Solutions for hydro-meteorological risk reduction in European and Global context		NbS, case studies (barriers for implementation and long-term monitoring)	Effects of forest fires on soil hydro-mechanical properties	Introduction to bio-mediated, bio-inspired soil improvement

Practicum				
Virtual reality of NBS for landslide risk reduction	Limit equilibrium method analysis for slope stability accounting for the effects of vegetation - SSAP software	Application of the LaRiMiT toolbox to a landslide case study	Forest cover effects on the occurrence of shallow landslide probability – the SlideforNet software	Ground improvement design

2 Structure of the excursions module

The excursions module provides a one-week program of field visits, possibly to sites that were introduced as case studies during the first week of the course. This module provides students with a valuable opportunity to directly observe and practically experience the physics of the phenomena at these locations.

Prior to the 2-week GEOMME course, participants are provided with an excursions guide, prepared by the organizers of the course in collaboration with relevant site contacts. This paper-based guide contains essential information about the sites to be visited, including technical descriptions of the landslide cases as well as the remediation or mitigation techniques, or monitoring set-up implemented at each site. For each site, references to scientific publications, websites, technical reports are also included. The outline of the excursions guide is the following:

1. Participants in excursions: list of participant name, affiliation and email address
2. Excursion route
 - 2.1 Excursion Itinerary: map view of the excursion sites, days and distances
3. Excursions plan: for each day, the following information is provided:
 - Schedule with important info (e.g. meeting place), map view of the itinerary
 - Technical description of the case studies: Introduction to the landslide case study, Cause of failure (predisposing factors, triggering factors), Geology and soil, Topography, Vegetation conditions, Remediation or mitigation measures, Discussions (e.g. warning and response issues, rainfall data inaccuracy, lessons learned)
 - References (e.g. scientific publications, websites, technical reports)

An overview of the excursion sites for the two years is provided in Table 9.

Table 9. Overview of the excursion sites visited in 2024 and in 2025, with a short description and relevant references

2024 course	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5
South Korea	Yecheon multiple landslides	Samga-ri landslide	Pyeongchang and Gangneung	Cultural Tour on the East Coast of Korea	National Institute of Forest Science
Description	15 debris flow landslides were triggered by heavy rainfall on the night of July 15, 2023, resulting in 10 fatalities and highlighting issues with the warning system.	The July 15 rainfall triggered landslides, with five source areas in the mountains. Saturated soil and rising groundwater caused sudden debris flooding and downstream damage.	The world's largest debris-flow experiment site in Korea allows analysis of flow characteristics and effectiveness of flexible and rigid barriers. Following, workshop at the Gangneung-Wonju National University.	Trekking at Seoraksan National Park Naksansa Temple	Introduction to the National Landslide Information System and visit to the Landslide Prediction and Analysis Center.
References	(Lee et al., 2024)		(Yune et al., 2023)	-	-

2025 course Italy	DAY 1 Bagno a Ripoli and Villamagna	DAY 2 NbS	DAY 3 NBS implemented in Portofino Natural Park	DAY 4 Pomezzana landslide and NbS at the Massaciuccoli	DAY 5 Monte Mario landslide area ISPRA
Description	Landslide stabilisation site with micropiles and live crib walls, vegetated grids and live planting, in a hillside area close to Florence. Live demonstration of field pull-out tests of tree roots in a forest in Villamagna	Nature-based Solutions in vineyards of Oltrepò Pavese (Northern Italy): state of the art and analysis of their effectiveness in shallow landslide mitigation	As part of the Horizon 2020 Reconnect project, San Fruttuoso implemented terrace restoration, traditional dry-stone walls, surface drainage, and soil bioengineering to reduce soil erosion	Visit to the landslide area restored with NbS. Insights from root system and evolution monitoring and its influence on slope stability NBS for erosion protection in the Massaciuccoli area, within the PHUSICOS project	Landslide after a fire in the Roman hillslope Monte Mario. Monitoring set up and programme for the landslide residual risk.
References	(Uzielli et al., 2025)	(Gambarani et al., 2025)		(Giachi et al., 2024) (Solheim et al. 2021)	

4 Critical assessment

4.1 Lecturers

Each course involves approximately 12 lecturers, with a total of 20 lecturers contributing over the two years, some of whom participated in both editions. Figure 2 illustrates the lecturers' backgrounds and a summary of their skills, highlighting that the course is primarily led by experts in geotechnical engineering, with a total of 15 experts. Complementary disciplines also play a significant role, including 1 lecturer from environmental engineering for NbS topics, forest engineering and geomorphology for forest management, and geology and engineering geology for early warning systems and landslide hazard assessment and management, respectively. In terms of country participation, South Korea and Norway contribute the most, accounting for 35% of the lecturers, followed by Italy at 15% (specifically for the 2025 course) and Japan at 10% (which instead was heavily involved in PD1 and PD2 on snow avalanches). Experts from various fields can be included as needed to enrich the course content, highlighting the importance of the interdisciplinary approach adopted.



Figure 2. On the left: distribution of lecturers' backgrounds within the group, and on the right: word cloud highlighting their skills (source: <https://www.researchgate.net/>)

4.2 Students' background

Each year, 3 to 4 students from each partner university are selected to participate in the project, with the selection process determined by the respective professor. The students may come from diverse backgrounds, including hydrogeology, geotechnical engineering, geomorphology, and geohazards. A key challenge in organizing the course is the creation of a content package that would bring everyone to the same level of knowledge. To address this, the online module provides an effective way for students to familiarize themselves with the topic prior to the beginning of the course.

4.3 The importance of the excursions module

The excursions module is a distinctive feature of this course, because it provides a unique opportunity for students to engage with case studies introduced in the lectures. In addition, the idea to develop it over one week, immediately following the lectures module, allows students to deepen their understanding of the topics, leading to a more meaningful participation in discussions. In previous editions, students demonstrated high levels of engagement, actively asking questions throughout the excursion. The excursions guide played a crucial role in facilitating the learning process, ensuring students could follow the on-site presentations.



Figure 3. Some pictures from the excursion week in 2024. Real scale debris flow testing facility with view of the gate for debris flow initiation, group photo at a landslide case and the runout area of the Yecheon landslide

4.4 Certification

Courses are designed to provide 5 ECTS credits under the European system. In practice, students apply for a "special pensum" and receive credits from their home institution upon completion of the required work. Evaluations typically consist of a summative written report on a relevant topic covered during the course. The assessment is conducted by two participating lecturers from the course.

4.5 Data management plan and sharable educational materials

The GEOMME project aims to promote knowledge sharing and educational equity by creating an open-access framework for course materials. Currently, all materials are systematically stored and managed within a centralized OneDrive repository, with access restricted to participants of the respective courses. These materials will eventually be hosted on a platform evaluated for sustainability, accessibility, and open-science compliance. This ensures secure interim storage while supporting long-term resource availability and reproducibility.

4.6 Lessons learned

The following points summarize the lessons learned during the GEOMME partnership for these PDs:

- interdisciplinary and practical focus: incorporating hands-on and interdisciplinary modules into the curriculum effectively bridges theoretical knowledge with practical, real-world applications, preparing participants to tackle complex geohazard challenges.

- participant engagement: active engagement from participants, through contributions to discussions and group exercises and activities, enhances both the learning experience and the networking for students and partners.
- integration of emerging geotechnics: presenting and implementing advanced tools and methodologies, such as machine learning and nature-based solutions, provides the students with a boost in emerging topics.
- online preparatory modules: providing foundational materials, including lectures, case studies, and software, prior to in-person sessions ensures participants are well-prepared and fosters a more effective learning experience.
- field-based learning: experiential learning through field excursions is invaluable, allowing participants to observe and connect theoretical concepts with practical, observable phenomena at case study sites.
- cultural and educational diversity: the international and interdisciplinary nature of the course enriches the teaching approach, fostering innovative solutions and collaborative methodologies.
- shared focus on climate change and sustainability: all GEOMME partner Countries recognize climate change as a major factor exacerbating geohazards, emphasizing the need for adaptive, sustainable solutions. The identification of unifying or common themes has contributed to the success of our activities so far.

5 Conclusions and GEOMME's legacy

This was the first partnership program ever coordinated by NGI on geohazard education, which allowed to strengthened collaboration between the three countries, leading to joint project proposals for continued research cooperation. Given the success of the GEOMME coordination, in 2022, NGI launched a new partnership with Brazil and India, coordinating the NATRISK project, which focuses more on risk management and resilience to natural hazards, integrating social science experts and stakeholder engagement, particularly in educating early warning systems and risk perception.

Acknowledgements

The authors would like to acknowledge the Research Council of Norway for funding the GEOMME and NATRISK partnerships (project numbers 322469 and 337241), as well as the Norwegian Directorate for Higher Education and Skills.

References

- Capobianco, V., Choi, C. E., Crosta, G., Hutchinson, D. J., Jaboyedoff, M., Lacasse, S., Nadim, F., Reeves, H. (2025). Effective landslide risk management in era of climate change, demographic change, and evolving societal priorities. *Landslides*. pp. 1-19.
- Capobianco, V., Uzielli, M., Kalsnes, B., Choi, J. C., Strout, J. M., von der Tann, L., Steinholt, I. H., Solheim, A., Nadim, F., Lacasse, S. (2022). Recent innovations in the LaRiMiT risk mitigation tool: implementing a novel methodology for expert scoring and extending the database to include nature-based solutions. *Landslides*, 19(7), pp. 1563–1583.
- DiBiagio, A., Capobianco, V., Oen, A., Tallaksen, L. M. (2024). State-of-the-art: Parametrization of hydrological and mechanical reinforcement effects of vegetation in slope stability models for shallow landslides. *Landslides*. 21(10), pp. 2417-2446.
- Gambarani, A., Vercesi, A., Bordoni, M., Giarola, A., Vivaldi, V., Meisina, C. (2025). Nature-based Solutions in vineyards of Oltrepo Pavese (Northern Italy): state of the art and analysis of their effectiveness in shallow landslide mitigation. EGU General Assembly 2024
- Giachi, E., Giambastiani, Y., Giannetti, F., Dani, A., Preti, F. (2024). Root System Evolution Survey in a Multi-Approach Method for SWBE Monitoring: A Case Study in Tuscany (Italy). *Sustainability*, 16(10), pp. 4022.

- Giadrossich, F., Schwarz, M., Cohen, D., Cislighi, A., Vergani, C., Hubble, T., Phillips, C., Stokes, A. (2017). Methods to measure the mechanical behaviour of tree roots: A review. *Ecological Engineering*, 109, pp. 256–271.
- Ham, S.-M., Martinez, A., Han, G., Kwon, T.-H. (2022). Grain-Scale Tensile and Shear Strengths of Glass Beads Cemented by MICP. *Journal of Geotechnical and Geoenvironmental Engineering*, 148(9), pp. 04022068.
- Kim, Y. A., Burrall, M., Jeon, M. K., DeJong, J. T., Martinez, A., Kwon, T. H. (2024). Pullout behavior of tree root-inspired anchors: development of root architecture models and centrifuge tests. *Acta Geotechnica*, 19(3), pp. 1211–1229.
- Lee, D. H., Kim, Y. T., Lee, S. R. (2020). Shallow landslide susceptibility models based on artificial neural networks considering the factor selection method and various non-linear activation functions. *Remote Sensing*, 12(7), pp. 1194.
- Lee, J. S., Song, C. H., Pradhan, A. M. S., Ha, Y. S., Kim, Y. T. (2024). Development of structural type-based physical vulnerability curves to debris flow using numerical analysis and regression model. *International Journal of Disaster Risk Reduction*, 106, pp. 104431.
- Lee, S., An, H., Kim, M., Eu, S. (2024). Preliminary analysis of nocturnal localized heavy rain-induced landslides in Yecheon County, Northern Gyeongsang Province, South Korea. *Landslides*, 21(2), pp. 429–435.
- Ramirez, R. A., Jang, W., Kwon, T. H. (2024). Wildfire burn severity and post-wildfire time impact mechanical and hydraulic properties of forest soils. *Geoderma Regional*, 39.
- Ramos, O., Kwon, T. H. (2023). Development of bio-grout injection strategy and design guide using reactive transport model for field-scale soil improvement based on microbially induced calcium carbonate precipitation (MICP). *Geomechanics for Energy and the Environment*, 36.
- Schwarz, M., Thormann, J.-J., Zürcher, K., Feller, K. (2012). Quantifying root reinforcement in protection forests: implications for slope stability and forest management. 12th Congress Interpraevent 2012. Grenoble, France.
- Solheim, A., Capobianco, V., Oen, A., Kalsnes, B., Wulff-Knutsen, T., Olsen, M., Del Seppia, N., Arauzo, I., Garcia Balaguer, E., Strout, J. M. (2021). Implementing Nature-Based Solutions in Rural Landscapes: Barriers Experienced in the PHUSICOS Project. *Sustainability*, 13(3), pp. 1461.
- Uzielli, M., Choi, J. C., Kalsnes, B. G. (2017). A Web-Based Landslide Risk Mitigation Portal. In *Advancing Culture of Living with Landslides*, The World Landslide Forum, pp. 431–438. Springer International Publishing. Ljubljana, Slovenia.
- Uzielli, M., Geppetti, A., Borselli, L., Renzi, S., Preti, F. (2025). Comparative geotechnical analysis of slope stabilization through conventional, soil and water bioengineering, and combined solutions. *Ecological Engineering*, 212, pp. 107487.
- Yune, C., Jeong, S., Mo Kim, M. (2017). Susceptibility Assessment of Rainfall Induced Landslides: A Case Study of the Debris Flow on July 27, 2011 at Umyeonsan (Mt.), Seoul, Korea. In *Proceedings of the 19th International Conference on Soil Mechanics And Geotechnical Engineering*. Seoul. South Korea.
- Yune, C.-Y., Kim, B.-J., Jun, K.-J., Park, S.-D., Lee, S.-W., Kim, G.-H., Lee, C.-W., Paik, J.-C. (2023). Real-scale experiment of debris flow in a natural gully: key findings and lessons learned. *Landslides*, 20(12), pp. 2757–2774.

Authors' bios

Vittoria Capobianco, Norwegian Geotechnical Institute – NGI (Norway)

Vittoria Capobianco is a Senior Engineer and Researcher in the Natural Hazards division at the Norwegian Geotechnical Institute (NGI) in Oslo, Norway. She holds a Ph.D. from the University of Salerno, specializing in the hydro-mechanical quantification of root effects in unsaturated soils. Her

research focuses on experimental monitoring and deterministic modelling of the effects of root reinforcement on slope stability at different scales, conventional and nature-based landslide mitigation measures, and the revegetation of industrial waste materials. She is member of the European Large Geotechnical Institutes Platform (ELGIP) working group on Climate Change Adaptation and is responsible for the 2025 GEOMME educational package. Her work spans applied research in EU, national, and international projects on nature-based solutions for natural hazard mitigation, alongside traditional geotechnical consulting projects.

Graham Gilbert, Norwegian Geotechnical Institute – NGI (Norway)

Graham Lewis Gilbert is a Senior Geoscientist in the Natural Hazards division at NGI. He is also an Adjunct Associate Professor at the University Centre in Svalbard - where he teaches topics relating to geohazards and adaptation. Graham has experience with hazard forecasting and multihazard and risk assessments. He is the coordinator of the GEOMME project and leads the project "Beredt! – Scalable Services & Risk-Based Governance for Climate-Driven Natural Hazards in Norway", financed by the Research Council of Norway (353197). He has extensive previous experience participating in and managing international and domestic research and consulting projects.

Luca Piciullo, Norwegian Geotechnical Institute – NGI (Norway)

Luca Piciullo is Associate Professor at OsloMet and Senior Specialist at the Norwegian Geotechnical Institute. His scientific activities focus on slope stability analysis and real-time forecast, IoT-based technologies and monitoring, rainfall thresholds, early warning systems, risk assessment, and tailings dam stability analysis. Luca serves as a distinguished expert adviser for Start FOREWARN and is a member of the executive committee of LANDAWARE. Furthermore, he is a member of the technical committee on Tailing and Mine Waste-ISSMGE and he seats in the Committee L – Tailings Dams and Waste Lagoons of ICOLD.

Tae-Hyuk Kwon, Korean Advanced Institute of Science and Technology -KAIST (South Korea)

Tae-Hyuk Kwon currently works as an associate professor at Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea. His research mainly focuses on three themes: energy geotechnology, bio-geotechnics, and natural geohazards. Specific emphasis is placed on prediction of landslides and debris flows, landslide early warning system, and debris flow mitigation measures. At a small length scale, he has a research program examining the bio-chemical processes in porous media at the pore- to core-scale using microfluidic chips and X-ray computed microtomography. At a bigger length scale, he also leads the projects related to remote sensing using drone-LiDAR system and satellite-SAR analysis for landslide analysis and detection, and underground tunneling using TBM. He is affiliated as a nominated member of TC306 geo-education, a corresponding member of TC308 energy geotechnics, and a corresponding member of TC104 physical modelling in geotechnics of International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE).

Ryoko Nishii, Niigata University (Japan)

Ryoko Nishii is an associate professor at Niigata University in Japan who specializes in the field of Geomorphology. She holds doctor of Science from University of Tsukuba. Her disciplinary research interests involve landslide processes and rockslope deformation prior to rockslide in humid and tectonically active mountain regions. Most of her work has conducted based on fieldwork including monitoring of unstable landslides, UAV- surveys, GIS analysis and dating. Due to her strong passion for teaching, she is also involved in education in hillslope disasters.

Naoki Watanabe, Niigata University (Japan)

Naoki Watanabe is an associate professor at Niigata University in Japan who specializes in the field of Groundwater Hydrogeology. He holds PhD in Science from Niigata University. His disciplinary research interests are in the influencing factors and the mechanisms of large-scale landslides in orogenic regions. Most of his work has been based on fieldwork including groundwater monitoring, hydro-chemical and

environmental isotopic tracer surveys, electromagnetic surveys, and dating. Due to his strong passion for teaching, he is also involved in the education of hydrology in the hilly and mountainous areas.

Joon-Young Park, Korea Institute of Geoscience and Mineral Resources – KIGAM (South Korea)

Joon-Young Park is a Senior Researcher at the Landslides Research Center of the Geologic Hazards Division at the Korea Institute of Geoscience and Mineral Resources. He earned his Ph.D. in 2019 from the Department of Civil and Environmental Engineering at the Korea Advanced Institute of Science and Technology. His research focuses on landslide prediction, specializing in early warning systems, monitoring, rainfall infiltration analysis, machine learning, unsaturated soil, debris flow modeling, and related experiments.

Marco Uzielli, University of Florence (Italy)

Marco Uzielli is an Associate Professor at the Department of Civil and Environmental Engineering at the University of Florence, Italy, where he earned his Ph.D. He was a post-doctoral scholar at the International Centre for Geohazards in Oslo, Norway. Prior to returning to academia, he served as specialist consultant in georisk analysis and probabilistic geotechnics for leading institutions worldwide. His current research, conducted in National and European research projects, includes the application of non-deterministic approaches to the geotechnical modelling of bioengineered solutions, modelling of geotechnical resilience, multi-risk analysis for geotechnical hazards, geotechnical performance-based analysis, and applications of machine learning to geotechnical engineering. He is involved in internal research projects involving the development, implementation, and assessment of innovative approaches to geotechnical education. In the context of such projects, he introduced blended learning approaches and novel grading criteria to foster students' agency in their university experience.

A 3-year multidisciplinary project training in Mining Engineering to build bridges across the disciplines

F. Descamps, N. Gonze, S. Vandycke, P. Ancia, T. Nikiema, O. Fay & J.P. Tshibangu

University of Mons, Mons, Belgium

fanny.descamps@umons.ac.be, nicolas.gonze@umons.ac.be, sara.vandycke@umons.ac.be,
philippe.ancia@umons.ac.be, tegawende.nikiema@umons.ac.be, ophelie.fay@umons.ac.be, jean-
pierre.tshibangu@umons.ac.be

ABSTRACT: Education in Mining Engineering and Geology at the University of Mons starts in the 3rd year of the Bachelor's degree in Engineering and continues during the 2 years of the Master's degree. Throughout this period, project-based learning provides students with a multidisciplinary education built around realistic mining engineering problems. Working in teams, students address complex engineering problems, tackling different aspects over time, thus breaking down the barriers between disciplines and reinforcing the links between geology, geomechanics and mining engineering subjects in the broadest sense of the term. This paper describes 4 types of projects that are carried out over the 3 years. Such projects encourage students to take a multidisciplinary approach of problems. Not only do they gain technical knowledge in different fields, but they also gain a better understanding of the interrelationships between courses. Furthermore, these projects develop essential non-technical skills such as teamwork, autonomy, a sense of responsibility, organisation and communication.

Keywords: Project learning, Multidisciplinarity, Rock mechanics, Engineering geology, Mine planning

1 Introduction

Project-based learning is widely used in engineering education (Airey, 2008). It is one of the pillars of education at the Faculty of Engineering, Mons (Belgium) for more than 20 years. Particularly in Geology and Mining Engineering, the industry demands highly multidisciplinary profiles, capable of solving complex problems, connecting various disciplines and acting with responsibility. This cannot be achieved through ex cathedra courses only.

Throughout the curriculum, project-based learning provides students with opportunities to tackle realistic mining engineering challenges, such as mine/quarry extension, creation of underground cavities, post-mining, environmental challenges, etc. These engineering problems serve as a general framework that students have to understand first. Then they handle several aspects of the projects like the ground model and constitutive laws, stability issues, design and construction of the works, planning, with a key principle in mind: creating bridges across the disciplines.

This paper first describes the educational framework at the Faculty of Engineering, Mons. Then, it focusses on the specific projects that are proposed in Mining Engineering and draws the lessons from this experience.

2 Faculty of Engineering, Mons and the Eng'Up approach

Higher education in the Wallonia-Brussels Federation is organised in terms of a credit accumulation system. An ECTS (European Credit Transfer and Accumulation System) credit is a unit of overall working time spent by the student, corresponding to 30 hours of learning activities (courses, practical

work, placement, etc.). This system focuses more on student learning. It is a central instrument of the Bologna process, which aims to make national systems more compatible.

In the Faculty of Engineering of UMONS (University of Mons), initial university education is organised in two stages: a “transitional” 1st cycle consisting of 180 credits, leading to a Bachelor's degree in engineering, and a “professional” 2nd cycle accounting for 120 credits, leading to a Master's degree. The first two years have a common curriculum for all Bachelors in Engineering (except Architecture). Seven different specialist areas are then proposed, among which Geology and Mining Engineering. Specialised courses are introduced in the 3rd year of the Bachelor's degree (45 ECTS).

The Faculty of Engineering is committed to an approach known as Eng'Up. It aims to provide future engineers with a high level of technical education and encourages them to question their future career. Eng'Up leads students to take on the course best suited to their personality. One of its key components is project-based learning, which starts from the 1st year of the Bachelor's degree (B1). Very early in the curriculum, students are led to actively discover the engineering professions and are introduced to project management through teamwork of 6 to 8 students. In B1 projects, they must produce a robot fulfilling an assigned mission identical to all teams. After 12 weeks, the robots participate in a competition that evaluates different aspects (performance, innovation, originality, weight and aesthetics). This project is based on the CDIO approach, standing for Conceive, Design, Implement, Operate (Crawley et al., 2014). This educational framework features an integrated curriculum with interwoven activities, rich design-build-test projects, and active, experiential learning. Skills like teamwork and communication are embedded.

In the 2nd year (B2), the same teams carry out a second project, this time on a subject they choose themselves, which also includes an entrepreneurial dimension. Here too, after 12 weeks, the project is evaluated on various criteria, in particular on the business plan, communication strategy, and relationship with potential customers. For both activities, a steering committee made up of teachers ensures the monitoring of the projects, as well as their final assessment. For the B2 project, members of a business incubator also attend the evaluation and select a team that is called upon to compete at the national level.

3 Mining-oriented projects in the curriculum

In Belgium, Geology and Mining engineers need to have a multidisciplinary profile that allows them to work in a variety of sectors, including mines and quarries (aggregates, building stone), cement production, metallurgy, energy sector (production, distribution), geotechnical consultancy, environmental assessment, education, etc. Besides general engineering courses, students are trained through the whole value chain of the mining industry, with courses covering fundamental geology, engineering geology, rock mechanics, mining techniques, mine planning, mineral processing, metallurgy, etc. Mining-oriented projects are introduced during the 3rd year of the Bachelor's degree (B3) with a geomechanics project and are pursued during the 1st and 2nd year of the Master's degree (M1, M2) with dedicated topics all linked to the same mining engineering problem (Figure 1).

Continuity of the projects through a variety of courses (geology, rock mechanics, mining, Table 1) is the core of this approach. The mining engineering problem is formulated in such a way that it will offer opportunities to be handled from various points of view, as shown in Figure 1. Continuity is also ensured by managing groups from one year to another. Groups of 3 to 4 students are created for the geomechanics project, and, as much as possible, group composition remains identical for the following projects. The implication (organisation, guidance and continuous feedback) of academics and scientists also contributes to the continuity among projects. Indeed, they are not involved in only one project type but follow at least two consecutive project stages, ensuring pedagogical coherence from one year to the next.

3.1. Geomechanics project

The geomechanics project represents the first steps of the students in this project learning in Geology and Mining Engineering. Rock mechanics and geology courses are introduced during the 3rd year of the Bachelor's degree. At this stage, students have some basic geological knowledge, and the geomechanics course has focussed on the constitutive laws of geomaterials and their characterisation both in laboratory and in situ.

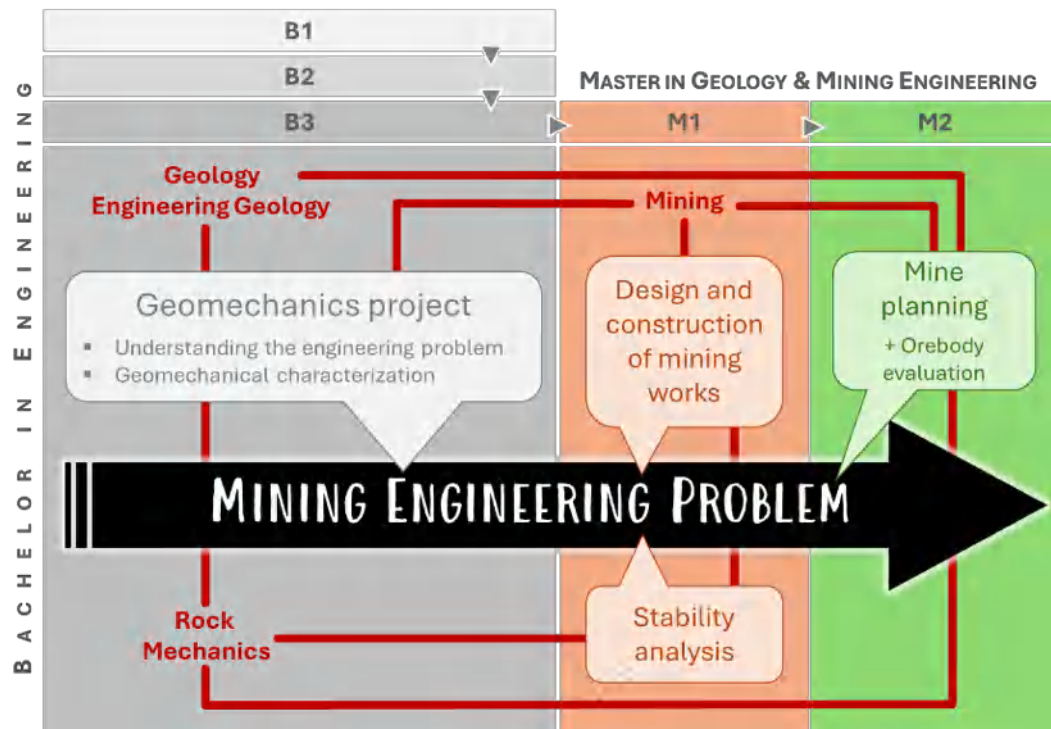


Figure 1. General organisation of mining-oriented projects during the curriculum

Table 1. Short description of teaching program in B3, M1 and M2 for Geology and Mining Engineering at UMONS. Only courses connected to the discussed projects are listed here

	Discipline	Course	ECTS	Hours Theory	Hours Exercises	Hours Practical work
B3	Geology	General geology	17	83	121	0
		Structural Geology				
		Geology of Belgium				
		Hydrogeology				
B3	Mining	Extraction of mineral resources	7	60	12	12 (visits)
		Principles of Mineral Processing				
	Rock Mechanics	Mechanical Behaviour of Geomaterials	3	24	12	0
		Project in Geomechanics				
M1	Geology	Geology Fieldwork	5	0	60	0
	Rock Mechanics	Analytical and Numerical Modelling in Rock Mechanics	9	28	24	0
		Design and Construction of Mining-Like Structures				
	Mining	Project Mine Planning and Optimisation	5	16	44	0

The objective of the project is to propose a constitutive model for the rock materials encountered in a typical mining engineering problem on a specific site. Detailed learning objectives are provided as supplementary material on <https://www.mygeoworld.com>, for all the projects described in this paper. During the first session, the general context of the mining engineering problem is presented: location, type of problem (see examples in Section 3.5), geological formation and possible outcrops, sources for literature review, working method and organisation.

First, students have to understand the engineering problem by identifying the relevant elements and by integrating them in a specific context (geological framework, environment, rocks involved). It develops their analytical mindset, using their current knowledge, and they complement it with additional reading, discussions with supervisors, and meetings with experts. Flipped classroom is particularly relevant for increasing their understanding of specific topics. Typically, students do not yet have skills in stability

analyses, but they are encouraged to include some readings on the topic in order to identify which information will be required to feed the models.

Second, acting as junior engineers, they determine which material(s) should be characterised, which tests are required, how and where to sample the rocks. Then, they proceed to in situ rock mass characterisations (structural survey, Rock Quality Designation, Rock Mass Rating) and laboratory tests. This organisation is very different from conventional laboratory sessions and quite confusing for students because it requires a high level of involvement. They are used to follow a pre-established program but, for the geomechanics project, they are asked to propose the testing program themselves. This shift promotes stronger project ownership. The staff is aware of the difficulty and iterates with students to reach an appropriate program.

The project includes dedicated sessions for literature review and additional lessons on specific topics, if needed. One or two days are also devoted to fieldwork on outcrops or in quarries for completing geological training, for rock mass characterisation and sampling. Students are also trained to sample preparation for mechanical tests and determine a multi-week work plan, including laboratory equipment scheduling. Collaboration between teams and pooling are encouraged.

Writing a scientific report is another objective of this project. Coaching is provided in terms of report organisation and presentation of data. Proofreading by teachers is proposed, with an intermediate deadline for the geological context. The final report should be about 50 pages for each group and is part of the assessment (see section 3.4).

3.2. Modelling, design and construction of workings

During the 1st year of the Master's degree, two projects are scheduled. One is addressing the stability of workings (rock slope, tunnel, shaft, underground cavity) and the other is dedicated to the design and construction methods required. Those two projects allow students to go deeper into their engineering problem, highlighting the transversality by combining several approaches (analytical and/or numerical modelling, sometimes empirical methods) and with both computational and technological concerns. Theoretical courses are partly given in advance so that students have the appropriate tools to handle the problems: stability of rock slopes from kinematic analysis, limit equilibrium analysis, analytical solutions for stresses around underground works, numerical methods (including finite element, boundary element, distinct element), convergence-confinement method in tunnelling, as well as the different underground construction methods, the various support systems, and their design methodologies.

Projects start after a few weeks of teaching and are conducted simultaneously, as much as possible, with the same groups as for the geomechanics project. This allows to use the results of stability analyses for the design and construction method, and vice versa, to come back to some computations for testing several designs. Typically, when support is required for underground work, students have to propose technical choices and have the possibility to validate their solutions in the numerical models.

The stability analysis project aims to develop students' ability to integrate geomechanical principles into engineering design. One key is to rely on the constitutive law obtained during the geomechanics project and to use it to feed the stability analyses. Students should also refer to their previous project for the geological and hydrogeological context, rock mass quality, topography, geometry of existing works, etc. and complete missing data. Numerical simulations are performed with the RocScience suite which offers a variety of tools, particularly for slope analysis and finite element modelling (FEM). One teaching objective is to connect theoretical principles of the FEM with its practical implementation.

The design and construction project aims to enable students to apply the concepts studied in class to the practical design of an underground structure. They are required to define the most appropriate excavation method for their project and design the support system to be implemented. This second aspect necessitates close collaboration with the modelling project to ensure that the chosen support system is well adapted to ground conditions. The ultimate objective is to produce a technical specification document detailing the excavation method, the type and design of the support system, and a construction schedule.

3.3. Mine planning project

During the 2nd year of the Master's degree, students undertake a project focused on the planning and optimisation of a mining operation, either for an open-pit or underground quarry/mine. The objective is to develop a long-term exploitation plan covering multiple years up to the end of the life. Whenever possible, this project is linked to previous ones, allowing students to build upon the projects from the 3rd year of the Bachelor's degree and the 1st year of the Master's program. This enables them to use geomechanical data and stability calculations for pit slopes or underground openings in order to design the necessary infrastructures for the operation.

Throughout the project, students use geological data (maps, drill cores) to develop a 3D geological model of the studied site. By integrating recent topographic data, they refine the geological representation and, when necessary, conduct an on-site survey using a total station available in the unit. Additionally, students apply geostatistical methods to model the spatial distribution of key parameters, such as mechanical properties or ore grade, within a block model of the deposit.

Based on this model, students design the future pits and determine the total life of mine according to the current production rate. To provide them with industry-relevant experience, all tasks are carried out using Surpac, a professional mining software developed by Dassault Systèmes.

3.4. Projects assessment

For all projects, assessment is based on a group report. Its size varies depending on the project. The report is a major target for the geomechanics project and a volume of 50 pages is required with a detailed description of the engineering problem, geological context, rock mass characterisation and laboratory testing to finally propose a constitutive law. For students, a page limit makes more sense than a word limit. It also includes figures and students must find a good balance between the text and illustrations, select the most relevant content and select which material is best suited for the main document or for appendices. This report should serve as a reference for the following projects. More concise reports are expected for Master's projects (typically 20 to 25 pages).

Assessment for the geomechanics project also includes an oral presentation by each team, followed by questions from the jury (academics and scientists involved in the project). All students attend the presentations. This is intended to train them for oral communication. For other projects, only questions and answers sessions are organized, without presentation.

Evaluation is partly based on a common mark for the group but also on individual grades. These individual grades depend on the student's commitment during the project (students working in the laboratory under teachers and scientists' supervision) and on the quality of their answers during oral examination. Combining a written report with oral presentation and discussion has proven to be a good means to assess each student's global involvement, rather than only evaluating a specific task. In addition, the teaching team closely monitors each group's progress throughout the project and pays attention to individual participation.

The geomechanics project is an independent teaching unit. Other projects are associated to courses with some theoretical assessment. Projects marks represent 40% (M1) to 50% (M2) of the total mark of the associated course.

In team works, a specific attention should be paid to ensure that each student really progresses and reaches the learning outcomes. This is accomplished through continuous supervision throughout the project. Formative assessment is time consuming but indeed very important to help student evolve in the good direction. Students know that assessment is not limited to the report, nor to the oral presentation but it is also a continuous assessment, including their active behaviour during the project sessions. Another aspect is that assessment is individual (which is partly possible because of continuous evaluation). Consequently, among a same group, some students may receive excellent grades while other could fail.

3.5. Some examples

3.5.1. Extension of a quarry

Open pit quarrying operations are typical mining engineering problems. In such cases, issues like the extension of the quarry (Figure 2), or the installation of new equipment serve as a realistic context for the projects. Outcrops for rock mass characterisation and sampling are generally easy to access. Students typically will investigate the geological context and propose a constitutive model during the geomechanics project to address the stability of benches during the 1st year of the Master's degree. The learning process continues with mine planning work in 2nd year of Master. For instance, Figure 2 b to d refer to quarries in Tournai area (Belgium) where two neighbouring pits are merging. This situation raises some issues on distribution of resources for aggregates and cement production, but also stability of the slope between pits and organization of access, evolution of the pit.

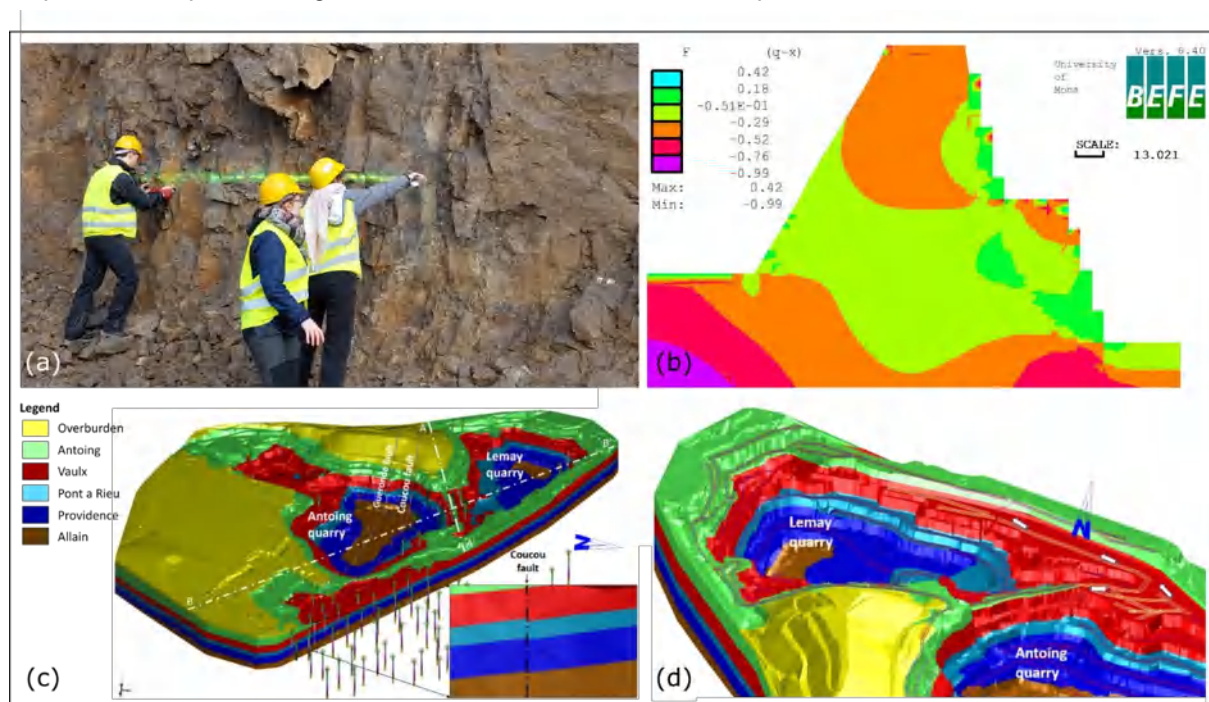


Figure 2. Example of projects dealing with quarries extension. (a) Rock mass quality assessment from a scanline and structural analysis of a quarry slope. (b) Finite element modelling of a slope between two quarries. Contour lines represent the value of the load function, positive values indicating yielding. (c) Geological model of quarries. (d) Planning of quarrying operation

3.5.2. Creation of underground works

Digging galleries, shafts, and underground cavities are typical mining-like underground works. Some recent students' projects involved such engineering problems, sometimes with quite original applications: digging new galleries in an old iron mine for water adduction, or the construction of a wine cellar in limestone formations (Figure 3). In the first example, the mining method has to be understood first, in order to identify how the new galleries could be dug. In the second case, students could benefit from the case study of a first cellar that was dug a couple of years before.

In 2025, B3 students start working on a challenging project, the Einstein Telescope, that will be Europe's most advanced observatory for gravitational waves. Their mission is to understand the purpose of such an ambitious project and particularly to focus on the 10-kilometers tunnels that will be excavated if the project is selected. For this study, students work on outcrops of the formations targeted by the current research teams in order to characterise the rocks and rock masses involved.

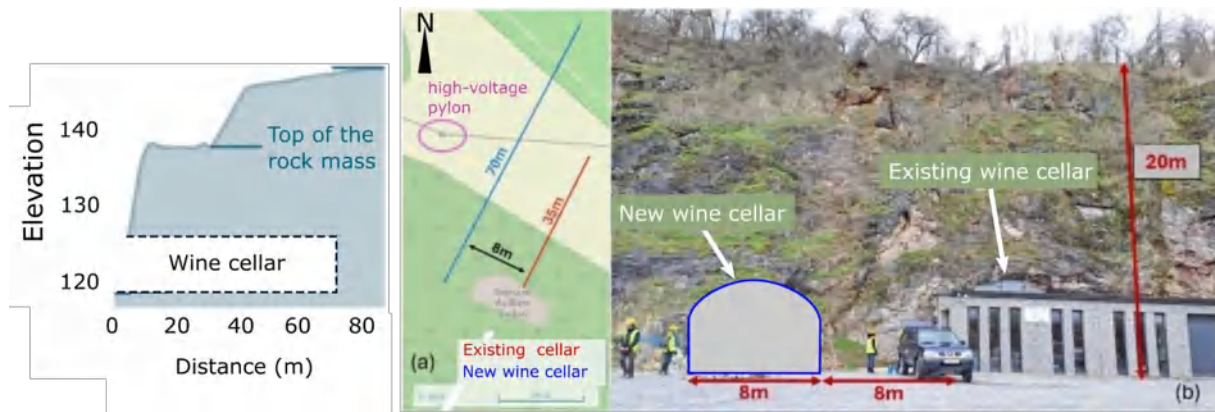


Figure 3. Example of a project dealing with the digging of a wine cellar in a rock mass. Focus on the design and construction project investigated by students. Left, profile of the cellar in the local topography. Centre, top view showing the trace of the existing cellar and the one delt during the project. Right, picture of the site with the design of the new wine cellar

3.5.3. Valorisation of underground cavities

Risks related to underground cavities are a concern in Wallonia, and improving their prevention and management was the core of the RISSC project (Georgieva et al., 2020; Kheffi et al., 2020). The valorisation of underground cavities has been highlighted as an alternative solution to mitigate such risks (Pinon, 2023). As an example, students were proposed to investigate the possibility of transforming an abandoned room-and-pillar quarry into an underground parking. During their geomechanics project, they had to rely on their mining course to understand how the room-and-pillar mining method is implemented, particularly from a stability point of view and associated geometry. They also collected documents about the abandoned quarry (history, maps, previous investigations) in order to propose a first solution for the parking. Another issue was to identify the geological formations and search for outcrops since the abandoned quarry is not accessible.

Once the rock has been characterised during the geomechanics project, the students' tasks in M1 were to address the stability of the proposed parking and also propose and test some designs for access roads and additional excavations.

4 Lessons learned

4.1. Bridges across disciplines

Building bridges across disciplines is one guiding principle of this project approach. Because skills integration and continuity between projects phases are required in professional life, our aim is to offer students a problem-oriented vision rather than illustrating courses one by one with different topics. Disciplines such as geology, engineering geology, rock mechanics and mining are introduced in B3 and are generally all connected to the geomechanics projects (Figure 1), as illustrated by the examples. Further teaching in M1 and M2 covers more specific aspects of the engineering problem and let the students understand the difficulties related to each discipline. Moreover, among those disciplines, students are provided a variety of skills, including both field and laboratory work, experimental and modelling aspects.

Such bridges across disciplines are also based on the documentation work for which students must process diverse materials (maps, drillhole data, books and scientific or technical papers, testing reports, etc.). Typically, drillhole data and geological maps need to be understood for building a suitable 3D model and description of the geological context.

The geomechanics project strongly supports the rock mechanics course in B3. This course focusses on the constitutive laws for geomaterials. Thanks to the project, students better understand the purpose of such a law and how its parameters can be obtained in laboratory. But they also highlight connections with geology, structural geology and even geotechnics.

In M1, the rock mechanics course is organized around stability analyses, either analytical or numerical. Similarly, students appreciate the project approach, in that some theoretical concepts become much clearer when applied to a practical case. The need for a constitutive model is obvious at this stage, clarifying the connection between B3 and M1 rock mechanics courses. Particularly, the project is organized before the course assessment and supports the understanding of the theory. Students consider that both projects proposed in M1 are closely related and again create bridges between (engineering) geology, rock mechanics and mining engineering courses. It helps to understand the link between the mechanical properties of the rock mass and the design of mining-type works.

Students also consider that the project approach allows to dive deeper into some topics. When specific questions arise on their project, it gives some opportunity to go beyond the course material, search for complementary data from teachers, experts or literature. Such behaviour is typical from inductive approaches to teaching and learning (Prince & Felder, 2006) and promotes intellectual growth.

4.2. Other lessons

Several strategies have been used for creating the groups and attributing the topics: random designation, team leaders who recruit their collaborators, concertation among all the students. Ensuring equity is a concern to “pull the students upward”. Even if the designation of team leaders seemed interesting, it did not show better results. Concertation among students is now the preferred method.

Good collaboration between teams is also observed. This is favoured by a real team spirit among students, and between students and academics, scientists and technicians. Each student can find his/her place in the team (field work, sample preparation, computations, writing report) and get better results when putting the group's skills together. Values such as sharing the knowledge, collaboration, respect of the others' work, communication are appreciated and contribute to enhancing motivation.

Project-based learning is also a good mean to promote autonomy and prepare students for their future work. Rather than a conventional laboratory session in which a list of precise tasks is prepared, here, the proposed topic is more general: propose a constitutive law for the geomaterials, investigate the stability of the work, etc. Autonomy is trained by asking the students to propose themselves how they could solve the problem. In B3 particularly, students often struggle to define their experimental program based on the engineering problem they investigate. Playing the role of a young mining engineer is confusing for them. They are more used to simply apply procedures rather than defining them. For instance, a challenge for students is to organise the laboratory work for several teams (preparing a planning for the use of equipment and staff so that everybody can work). In the Master's degree, students are much more autonomous and do not hesitate for distributing tasks among the team. With time, students become more aware of their strengths and weaknesses and become able to rely on the team to produce more efficient work.

Projects are also organised with some contribution of the industry sector, by involving some experts for specific topics, by integrating current issues of the industry into the project topics, or simply to have access to sampling sites in quarries. Including the students in this interaction between academics and professionals is important. It prepares the young generation for becoming responsible engineers, as requested by future employers (profession advisory committee) and as promoted by the Eng'Up approach.

4.3. Students' perceptions

To assess students' perceptions of the projects and their impact on their learning process, a survey was conducted anonymously as a Wooclap poll. Students received a QR-code and submitted their answers digitally. The survey used yes/no questions, but students could add a comment if they wished. 10 students participated, among a group of 12 Master students (M1 level), i.e. 83% of respondents. The Authors did not propose the poll to Bachelor students because they had not yet experienced the mining-oriented project approach at this time of the year, nor to M2 students because the group was too small to ensure anonymity. Students often provided additional comments, enriching the results discussion.

Figure 4 summarises the key findings of this survey, presenting the percentage of students who positively evaluated each aspect of the projects. The results highlight that students highly value the projects in terms of problem identification, work planning, and knowledge acquisition, particularly regarding geomechanics, modelling, and design and construction aspects.

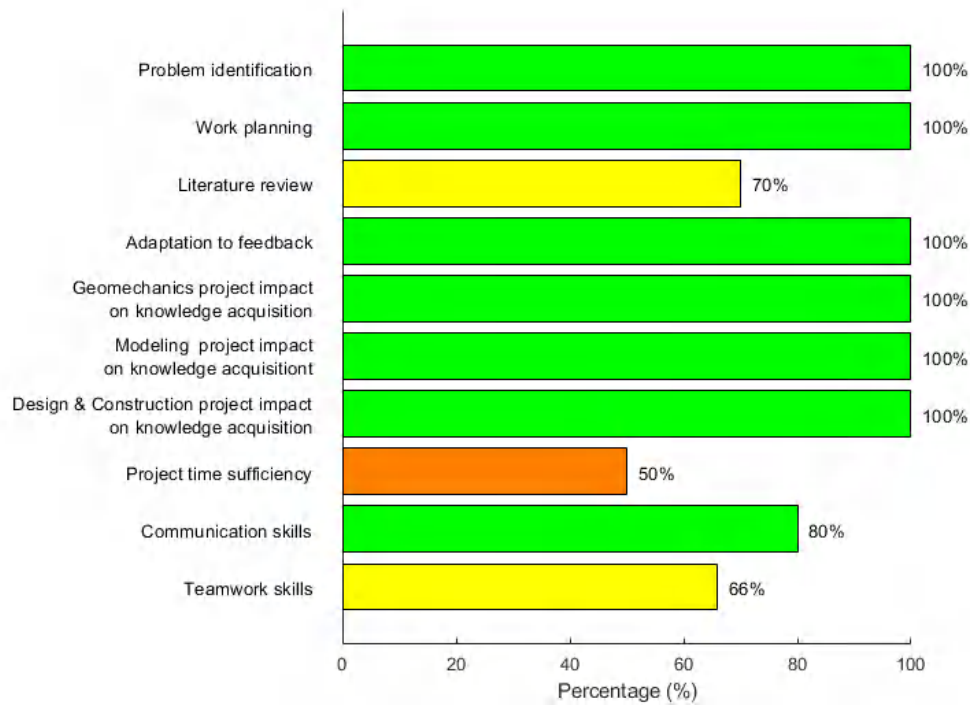


Figure 4. Summary of survey results on students' perception of the projects. Percentages indicate the relative amount of students who positively evaluated a given outcome of the projects

The projects were widely appreciated for reinforcing theoretical knowledge through practical application. Students reported that working on geomechanics, modelling, design and construction projects helped them better assimilate course content. The hands-on nature of these assignments allowed them to visualize concepts and apply them to real-world scenarios, significantly improving their understanding.

Beyond technical knowledge, students developed valuable skills in problem identification, work planning, and research methodologies. Many improved their ability to structure tasks, manage deadlines, and collaborate effectively within teams. The need to gather relevant documentation also encouraged students to explore academic and industry sources, enhancing their research competencies.

Another strength was the constructive use of feedback. Iterative reviews from professors and teaching assistants helped students refine their analyses, improve report clarity, and adopt a more structured approach to problem-solving. This process fostered precision in technical explanations and deeper engagement with engineering methodologies. Additionally, report writing and presentations strengthened students' communication skills, while teamwork encouraged critical thinking and collaboration. Most students agreed that these projects provided a valuable platform for articulating ideas, debating technical choices, and working collectively toward a common goal.

Despite these strengths, students identified several challenges. The most frequently mentioned issue was time management. While some found the project duration sufficient, others felt overwhelmed, especially when balancing project work with a demanding course schedule. Several students suggested starting projects earlier in the academic year to distribute the workload more effectively. The high time demands of projects is often reported as a disadvantage of project-based learning (not only for students but also for the staff), as well as less rigorous understanding of engineering fundamentals (Airey, 2008). These drawbacks are counterbalanced by more conventional lectures that are organised in parallel. Indeed, in our framework, projects do not substitute to lectures but complement them.

Although the projects promoted independent research and work, several students reported difficulties in navigating academic literature and in using specialized software or laboratory equipment. To address the issues related to academic literature review, a dedicated training session on academic databases was introduced in 2024-2025 for B3 students, in collaboration with university librarians. In addition, a concise writing guide is available to help students structure and present their scientific reports more professionally. Regarding mastering software and laboratory tools, students can make progress thanks to individual coaching and dedicated tutorials. Their feedback remains instrumental in identifying the areas where they face the most difficulties, thus informing and refining our pedagogical strategies.

Regarding teamwork, most students were satisfied with the current group formation method and preferred to keep it unchanged. However, some noted challenges in ensuring equal participation, as smaller teams sometimes led to workload imbalances. In some cases, one or two members carried a disproportionate share of the work.

Overall, the survey confirms that project-based learning is perceived by mining engineering students as highly beneficial, enabling them to apply theoretical knowledge, develop problem-solving skills, and improve their teamwork and communication abilities.

5 Conclusions

The Faculty of Engineering at UMONS is committed to an approach known as Eng'Up. It aims to provide future engineers with a high level of technical education and encourages them to question their future career. One of the keys to this approach is project-based learning. In Geology and Mining Engineering especially, this is developed via a multidisciplinary project approach from the 3rd year of the Bachelor's degree to the 2nd year of the Master's degree. The geomechanics project in B3, the design and construction and the stability analysis projects in M1, and finally the mine planning project in M2 form a continuous education package connecting many disciplines. It aims to prepare students to their future job by means of a typical mining engineering problem for which they investigate various aspects year after year, developing both their technical and soft skills.

Student feedback on the project-based learning approach has been largely positive. Students particularly value the opportunity to apply theoretical knowledge to practical problems, which reinforces their understanding of course material. They also recognize the development of crucial skills such as problem-solving, work planning, teamwork, and communication. While challenges related to time management and navigating academic literature have been noted, these are being addressed through pedagogical adjustments.

Acknowledgements

The authors would like to thank the students for their valuable feedback.

References

- Airey, D.W. (2008). A project based approach to teaching Geotechnical Engineering. Proceedings of the 1st International Conference on Education and Training in Geo-Engineering Sciences, Manoliu I. & Radulescu N. (Eds), pp. 357-362, Taylor & Francis Group, London, UK
- Crawley, E. F., Malmqvist, J., Östlund, S., Brodeur, D., Edström, K. (2014). Rethinking Engineering Education – The CDIO Approach, 2nd ed., Springer-Verlag, New York, USA.
- Georgieva, T., Descamps, F., Gonze, N., Vandycke, S., Ajdanlijsky, G., Tshibangu, J.P. (2020). Stability assessment of a shallow abandoned chalk mine of Malogne (Belgium). *European Journal of Environmental and Civil Engineering*. 27(6), pp. 2358–2372.
- Kheffi, A., Watelet, J.M., Lefebvre, C., Deudon, A., Dubois, M., Descamps, F. (2020). RISSC : mieux gérer les risques liés aux cavités souterraines en Wallonie et dans les Hauts-de-France. Proceedings of « Dixièmes Journées Nationales de Géotechnique et de Géologie de l'Ingénieur : L'Innovation et la Formation pour relever les défis de demain », Bernhardt, V., Sulem, J., Cosenza, P., Deveze, G., Briançon, L. (Eds.), 8 p., CFMS, CFMR, CFGI, Lyon, France.
- Pinon, C. (2023). La valorisation des cavités souterraines : une solution alternative de mise en sécurité. Report, Interreg France Wallonie Vlaanderen project RISSC, 24p.
- Prince, M.J., Felder, R.M. (2006). Inductive teaching and learning methods: Definitions, comparisons and Research, *Journal of Engineering Education*, 95(2), pp. 123-138.

Authors' bios

Fanny Descamps, University of Mons (Belgium)

Dr Ir Fanny Descamps is associate professor at the University of Mons, Belgium, and head of the Mining Engineering unit. She graduated as a Mining Engineer (M.Sc., 2002) and achieved a PhD in rock mechanics as a research fellow of the FNRS (Belgian Fund for Scientific Research). She continued as a post-doctoral researcher, specialising in the constitutive behaviour of rocks. After that, she has been involved in several projects, diversifying her research interests. Particularly, she worked on risk related to underground cavities, on the relations between geology and geomechanics in chalk and on several mine planning projects for quarries in Belgium. During her early career, she already participated to many teaching tasks, understanding the importance of multidisciplinary for future mining engineers and the connections between academia and industry. She is now teaching rock mechanics and reservoir engineering at UMONS for students in Bachelor's and Master's degrees and continues her involvement in transversal courses. She is a member of ISRM and IAEG, and member of the WEG committee (Women in Engineering Geology).

Nicolas Gonze, University of Mons (Belgium)

Dr Ir Nicolas Gonze is a lecturer and teaching assistant at the University of Mons in the Mining Engineering unit. He holds a Master's degree in Geology and Mining Engineering (2013) and earned his PhD in 2022 from UMONS. His doctoral research focused on understanding the rock cutting mechanisms under confinement. After an experience in the recycling industry, he joined the Mining Engineering unit in 2014 as a teaching assistant and PhD candidate, contributing to various mining engineering courses. Today, he teaches "Design and Construction of Mining-Like Structures" and "Mine Planning" to Master's students, guiding them through both theoretical concepts and practical applications. Passionate about education, he encourages students to move beyond compartmentalised knowledge and forge meaningful connections between their courses. His goal is to equip them with a holistic understanding of the challenges in rock mechanics and mining operations, preparing them to tackle complex real-world problems with confidence and insight.

Sara Vandycke, University of Mons (Belgium)

Dr Sara Vandycke is Research Associate of the Belgian Fund for Scientific Research (F.R.S.–FNRS). She is structural and tectonician geologist, specialised in natural fracturing, jointing and faulting in carbonated rocks. She has a strong experience in paleostresses analysis in chalk, connecting to regional geodynamics in northwest Europe. She is also teaching structural geology and cartography at the University of Mons.

Philippe Ancia, University of Mons (Belgium)

Dr Ir Philippe Ancia is an Engineering Geologist (University of Liège, 1987) and PhD since 1993 (University of Liège). Since September 2002, he has been a professor in the Mining Engineering unit of the University of Mons (UMONS), where he mainly teaches to students in Geology and Mining Engineering. His main areas of teaching and research are the processing of mineral materials and waste, environmental problems related to these activities and the treatment of polluted soils. He is also involved in the projects organised in the 1st and 2nd year of the Bachelor's degree, ensuring a better understanding of the students' background when they join their specialisation in Geology and Mining Engineering.

Tégawendé Nikiema, University of Mons (Belgium)

Ir. Tegawende Nikiema is a teaching assistant and PhD student, at the Faculty of Engineering of the University of Mons, Belgium. He holds his Master's degree in Geology and Mining Engineering since 2022, from the same faculty. He is involved in several teachings in the Mining Engineering unit, namely geomechanics, mining construction, mine planning and mineral processing. His research topic deals

with the understanding of the mechanical behaviour of fractured rocks and their integration into numerical geomechanical modelling, with a particular focus on the effects of roughness.

Opélie Faÿ, University of Mons (Belgium)

Dr. Ophélie Faÿ is a FNRS post-doctoral researcher working at the University of Mons. She joined the Mining Engineering unit in 2023 and holds a PhD in Geology from KU Leuven. Her research focuses on chalk, studying how sedimentology and diagenesis affect its properties. Recently, she has been exploring how water saturation impacts geomechanical properties, with applications in reservoirs, hydrogeology, geothermal energy, carbon storage, and the stability of underground structures. Dr. Faÿ is also passionate about teaching, guiding students in fieldwork and practical courses. She emphasises the importance of connecting different disciplines in both her research and teaching, helping students understand the broader implications of geological processes.

Jean-Pierre Tshibangu, University of Mons (Belgium)

Dr Ir Jean-Pierre Tshibangu is emeritus professor of the University of Mons where he was head of the mining engineering unit for more than 25 years. Graduated as a mining engineer from the University of Lubumbashi, he first gained experience in the mining industry in DRC before obtaining a PhD degree from the Faculty of Engineering, Mons. Passioned about engineering sciences, he taught a wide variety of disciplines in the fields of rock mechanics and mining sciences, while contributing to cutting-edge research in those disciplines as well. Committed to the evolution of the teaching programs in the University of Mons, he introduced the project-based approach presented in this paper in the early 2000's. He is still strongly involved in the scientific activities of the mining engineering unit, and in university cooperation with DRC, while keeping strong relationships with the industry.

Geotechnical engineering knowledge base needed for the improvement of mine tailings safety

B. Kovacevic Zelic¹, M. Burecic Safran² & D. Znidarcic³

¹University of Zagreb, Zagreb, Croatia
biljana.kovacevic-zelic@rgn.unizg.hr

²Zagreb University of Applied Sciences, Zagreb, Croatia
mirela.burecic.safran@tvz.hr

³University of Colorado, Boulder, USA
dobroslav.znidarcic@colorado.edu

ABSTRACT: Due to the increased quantities of mine waste, the expected increase of number, size, and complexity of the tailings dams in the future and their unfavourable failure rates statistics in the past, global consensus has been achieved that certain improvements are needed considering the management of human resources within the mining industry, especially associated with the mine waste management. The design, construction, maintenance and after-care of tailings storage facilities (TSFs) are complex tasks that require expertise predominantly in mining and civil engineering with the contribution of various other disciplines. This paper will focus just on one aspect of "tailings engineering" education, i.e. how to develop a proper geotechnical engineering module within mining/civil engineering programs at graduate level for future generations of engineers to whom the main roles and responsibilities could be assigned at TSFs. The additions that are required for "tailings engineering" to the basic soil mechanics course, which is taught at most mining/civil engineering curricula, will be discussed. The proposal of several informative graphics will also be shown that could be used at graduate level to critically examine some commonly accepted concepts from soil mechanics or to attract more candidates to such a challenging specialization.

Keywords: Mine waste, Tailings, TSF-Tailings storage facility, Burland's triangle

1. Introduction

There are various engineering structures constructed in mining applications where the knowledge of soil mechanics and other related geotechnical courses is essential. Tailings storage facilities (TSFs) rank among the largest man-made structures on the Earth and are used to store the byproducts of mining processes. They are frequently referred to as "hybrid" facilities because they integrate both mining and civil engineering disciplines. Mining engineers' expertise encompasses understanding the composition and properties of tailings materials, the volume and rate of tailings production, and its transport and deposition into the impoundment area. Their critical role is to ensure that tailings are deposited in a manner that supports TSFs' structural integrity. Civil engineers, on the other hand, are responsible for the design of the tailings dam structure itself, considering factors like settlement, stability, seepage, and seismic loading, taking into account that important aspects of tailings behaviour must be understood, such as consolidation, desiccation and creep behaviour of highly compressible tailings (Fourie et al., 2022). Moreover, unique behaviours of various types of tailings, combined with the challenges of construction in an often remote and harsh environment, make interdisciplinary collaboration imperative to ensure long-term robustness of tailings dams.

The design, construction, maintenance and after-care of TSFs are complex tasks that require the expertise predominantly in mining and civil engineering disciplines with the contribution of various other

disciplines such as geology, hydrology, hydrogeology, geotechnical and environmental engineering, geochemistry, etc. Apparently, the roles of certain specific professionals are clear. Nevertheless, there is a number of reasons indicating that further improvements are needed in the education and practice related to the management of various types of mining waste and TSFs:

- There are thousands (estimates range from 2000 to as much as 15000) dams holding mine waste all over the world, among which only several hundred are built in the past 10 years (Davies, 2002; Spencer et al., 2021). Many old dams probably need to be re-evaluated, which applies especially to the upstream constructed dams as the most vulnerable type.
- Accidents and failures at TSFs continue to occur at an unacceptable rate. The failure rate of tailings dams is estimated at 1,2% globally over the last hundred years and is much higher than for conventional water retention dams (estimated at 0,01%). Moreover, some of these failures caused severe economic and environmental impacts, and unfortunately loss of lives (Azam & Li, 2010; Davies, 2002; ICOLD, 2001).
- The analyses of the failure modes show that most failures could have been foreseen and prevented by applying classical civil or more specifically geotechnical engineering knowledge related to design, construction or maintenance of TSFs (Rana et al., 2021; Stark et al., 2022). More specifically, the most common causes of tailings dam failures are slope instability due to static or dynamic loading (earthquakes, mining operations), insufficiently explored or weak foundations, water-related problems (overtopping, seepage, erosion) or poor construction quality control (materials and procedures).
- Taking into account the increasing demand for mineral raw materials worldwide and considering various natural (missing or lower grade natural deposits) or geopolitical causes (transport blockage) that can disrupt it, in the future not only natural deposits, but also man-made deposits and fills (various types of waste) can be considered as potential sources for mineral raw materials production. Consequently, the quantities of various types of mining waste including tailings and hazardous waste are going to increase further. The size, number and complexity of TSFs are going to increase as well.
- TSFs are mostly built in remote areas and in challenging environments (harsh climate or difficult morphological conditions, missing infrastructure and lack of construction materials, etc.). They are commonly built by mine operators using tailings as a construction material.
- Legal and social aspects for the TSFs development and maintenance might be restrictive: requirements to minimize water and energy consumption, to reduce land disturbance, to minimize the impacts on the air, surface and ground water quality, etc.
- TSFs mostly have a very long lifetime (active and post-closure) during which legal, economic, social, technical, environmental and other contexts can change indicating the importance of data and human resource management. Tailings dams are designed to last the life-of-mine (LOM), which regularly cannot be predicted with a high degree of certainty, and with stages built in over long periods of time (up to 50 years or more). In some countries post-closure lifetime is prescribed to hundreds or even thousands of years.

The ICOLD Bulletin 121 (ICOLD, 2001) has documented over 200 case records of failures/incidents at TSFs and concluded that *“the adequate and enforced application of available engineering technology to the design, construction and closure of tailings dams and impoundments”* must be achieved. Unfortunately, failures of TSFs continue to occur. Several catastrophic TSF failures in the last ten years have become a turning point in raising global awareness about dams that pose dangers to both people and the environment. The positive effect of these catastrophic events was that in August 2020, the GISTM (Global Industry Standard on Tailings Management) was published as a benchmark for the mining industry (GTR, 2020). Among other things, that document defines key roles and functions at TSFs together with key documents that have to be developed and regularly updated over the TSF lifetime. The GISTM does not strictly define a required profession for holding any of the following roles: Responsible Tailings Facility Engineer (RTFE), Engineer of Record (EoR), Designer of Record (DoR), senior independent technical reviewer, or member of the independent tailings review board (ITRB). However, the general term “engineer” is used. This clearly indicates that various disciplines can participate, but that the appointed person should possess sufficient knowledge to tackle such challenging projects. In practice, very often at least on the side of the mining company or the operator of the site, those positions are held by persons having mining engineering background.

In summary, there has been an understanding for a long time of the problems associated with the tailings management and the awareness about the need for a multidisciplinary approach towards the solutions. On the other hand, the fact that statistics of failures and accidents have not significantly been improved also shows that further steps are needed by joint efforts of operators, regulators, educators and others. This article will discuss the geotechnical engineering knowledge base needed for the improvement of mine tailings safety by providing some initial ideas of what should be included into education at the graduate/master level of engineering, and how generally accepted concepts of certain specific professions should be critically examined, with the aim of gaining an initial insight into engineering challenges associated with tailings management and encouraging a desire for further involvement in finding solutions to related problems.

Current status and future prospects

It is already globally recognized that certain improvements are needed concerning the management of human resources within the mining industry especially associated with the mine waste management. Mine waste and TSF management is a multidisciplinary task, as explained in the introduction. In the article, this issue will be looked at from the higher education perspective only. There are different approaches on a global scale towards education at the interface of mining, geotechnical and environmental engineering related to mine waste management. Some universities are offering certain study programs that link up “mining and geoenvironmental engineering”. Other universities or organizations offer specialized lifelong learning programs for sustainable mine waste and TSFs management.

It is also important to mention that most countries are faced with a lack of interest for the study of mining, mineral and metal processing or engineering in general. On the other hand, the problem of missing skilled professionals is globally present, especially because more sophisticated methods of extraction and processing of ores/fills are going to be needed as the quantity and quality of available natural resources decreases. At the same time, the production of mine waste dramatically increases. Consequently, the shortage of highly specialized tailings engineers is also high. According to some sources, several thousands of engineers are lacking globally (Leonida, 2020). It is therefore of equal importance to find ways on how to attract younger generations to find their perspective in such a challenging industry.

Looking at mining engineering curricula offered worldwide, it can be concluded that contents related to geotechnical engineering, soil mechanics, surface and groundwater management and environmental geotechnics are marginally present. Obviously, it is not an easy task to balance the contents needed for the core mining business and so highly specific skills are required for the safe design, construction, maintenance and after-care of TSFs. On the other hand, at civil engineering programmes geotechnical aspects are much more present in regular curricula. Nevertheless, considering the origin of tailings materials, their specific physical, mineralogical and chemical properties, unique mechanical behaviour and the complexity of TSFs (variability in space and time), the usual geotechnical engineering programmes again do not cover such specific contents.

This paper focuses solely on one aspect of “tailings engineering” education, i.e. how to develop a proper geotechnical engineering module within mining/civil engineering programmes at the graduate level for future generations of engineers to whom the main roles and responsibilities will be assigned at TSFs. Such a program would have to cover some major issues in tailings management such as laboratory and in-situ characterization and classification, site selection, water management and seepage control, stability and settlement/consolidation, monitoring/surveillance, and finally closure of TSFs. This list demonstrates that a tailings engineer should follow almost the same approach as the geotechnical engineer in any other construction project. However, there are also significant differences in each stage of the TSFs projects. This paper tries to summarize these similarities and differences. In more detail, the additions to the basic soil mechanics course, which is taught at most mining/civil engineering curricula, that are required for tailings engineering are suggested. The proposal of several informative graphics, which could be used in the education of mining/civil engineers at the graduate level to critically examine some commonly accepted concepts from soil mechanics, are shown. Advanced theories/skills will not be covered because they fall outside the scope of this article and are included in specialized study programmes and life-long learning education.

Inverted TSFs triangle

As has already been discussed in the introduction, most of the documented TSF incidents happened due to incomplete adherence to the design (often provided by external companies), poor construction and maintenance control (construction materials, water control, etc.) or a general lack of understanding of the key features that control safe operations (seepage, erosion, stability, etc.). Driven by the idea of Burland's geotechnical triangle (Burland, 1987; 2012) and problems experienced in practice, the inverted TSF triangle is proposed (Fig. 1) together with the explanation of the major differences in the framework of mining/civil engineering programs pertaining to the knowledge needed for safe, stable and environmentally acceptable TSFs.

On the upper vertices of the inverted TSF triangle two aspects considered to be of equal importance are set. The first one is the origin, characterization and classification of materials that are present at TSFs. The second one is related to water management and seepage control. The third, bottom vertex is related to the engineering behaviour and modelling of tailings. In the middle of the triangle practical aspects of TSFs are positioned, which include all phases of planning, development, maintenance and after-care of TSFs. The triangle should be enfolded into the cloud of sustainability and environmental soundness, as all the phases in the lifetime of TSFs are largely determined by the principles of sustainability, social and environmental acceptability.

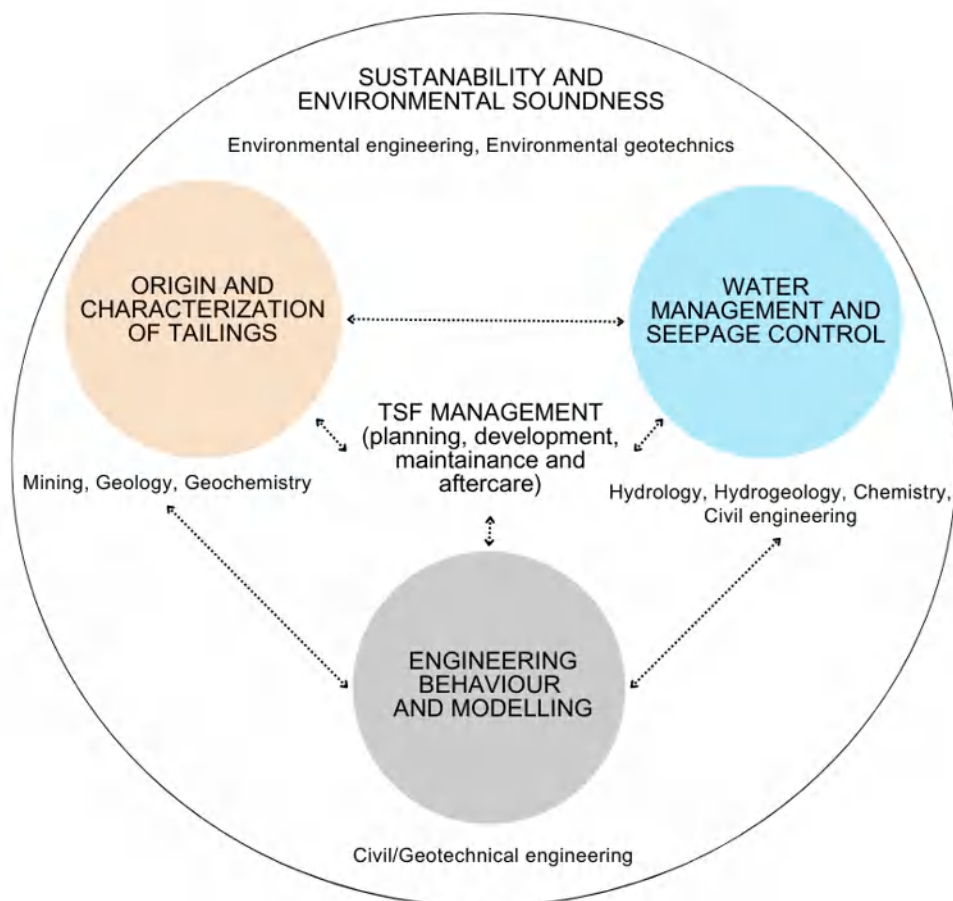


Figure 1. Inverted TSFs triangle

The ground profile as defined by Burland is the description of different layers together with groundwater conditions, as a result of geological processes and man-made activities obtained by ground exploration (Burland, 1987). For TSFs, besides the geological setting and characterization of geological materials in the foundation, there is a need to obtain physical, mineralogical/chemical and design properties of tailings. Although tailings originate from the natural rock materials, they possess quite different properties compared to natural soils. Therefore, additional characterization techniques are often required. Moreover, spatial and temporal variability of properties is more pronounced at the TSFs due to the changes on the market and within the processing plant.

For the water management and seepage control, there is also a need to include additional data considering water balance (inflow and outflow to/from the processing plant), water chemistry and geochemical considerations, and seepage and interactions with various construction materials. This also means that the processing plant water, groundwater, as well as construction and foundation materials must be physically and chemically characterized.

Considering engineering behaviour and modelling, for the interpretation of tailings behaviour proper application of classical soil mechanics theories requires accounting for the unique properties of tailings and recognizing that there are cases where the classical soil behaviour theories may not apply in their conventional sense. Not only do tailings vary depending on the processed ore materials, but they can also differ significantly depending on the processing method used. In addition, properties within an ore body and the same processing plant can change over time. Fourie et al. (2022) elaborated major differences in the properties of tailings in comparison to natural soils. Consequently, for certain types of tailings obtained from hard parent rocks conventional consolidation theory is applicable. However, for tailings deposited at large void ratios and characterized by stress dependent permeability, instead of traditional small strain consolidation theory, a nonlinear finite strain consolidation theory should be used. The importance of the appreciation for the specific hydraulic behaviour of tailings is even more significant for seepage and stability analyses. The permeability of tailings exhibits significant anisotropy, stress and saturation dependency, mainly due to depositional procedures, and this must be considered in the seepage calculations. Tailings are also characterized by loose, contractive behaviour and brittle failure. It is therefore worth examining whether limit equilibrium methods/pseudo-static analysis or more sophisticated numerical modelling should be used for stability calculations and how to determine proper design parameters.

From the practical point of view, again there are certain very specific conditions and requirements when the TSF projects are to be implemented from the planning to the aftercare stage, which will be emphasized here. The siting of TSFs is almost as a rule connected to remote locations and harsh conditions. The main criteria for the TSF site selection are the distance and relative elevation to the plant. Other less important criteria are topography, hydrology, geology and groundwater factors, which is unusual for most other engineering projects. In the construction stage, the questions of the building materials availability and compaction control go hand in hand with the staged construction over very long periods of time.

Mining activities today are expected to be conducted in accordance with the principles of sustainability. In other words, mining projects should be financially viable, technically appropriate, environmentally sound and socially responsible. However, they are characterized by very long-time frames (for some commodities active lifetime can be more than 100 years). In such a time frame various changes are to be expected, which can hardly be predicted in all aspects. Sustainability and environmental soundness for TSFs may be best problematized on the planning for the closure and post-closure phase. In some countries 1000 years is established as the post-closure period. This means that TSFs must be designed to contain tailings indefinitely, minimise long-term environmental impacts, and achieve a self-sustaining solution.

Main processes and operations that occur throughout the lifecycle of TSFs are listed in previous sections. Inverted TSFs triangle (Fig. 1) could also be used to clarify which processes are better understood by mining/civil/geotechnical engineers and which by engineers of complementary scientific fields. It can also be used to explore the extent to which these disciplines can overlap in their responsibilities and whether, due to the specific nature of the situation, different professions should have a comprehensive understanding of all processes. However, the focus will be further directed to the education of engineers that could meet the needs for effective tailings management. The logic of Burland's triangle, which covers all the main aspects of geotechnical engineering and can be used to develop either a whole geotechnical engineering study program or a soil mechanics course, is applied to tailings engineering. An explanation will be given on how the inverted TSF triangle could be used for the comparison of the available mining/civil engineering curricula with the knowledge base needed for TSF management. Moreover, it will be shown using several examples how some well-established concepts/theories from soil mechanics or mining/civil engineering should be shaken up and critically examined if applied to TSFs.

8.1 The origin and characterization of soils and tailings

Most of the books used for teaching soil mechanics at graduate programs define soils as unconsolidated particulate geological materials formed by physical, chemical and biological weathering of rocks (Budhu, 2000). For civil engineering students, soil as a three-phase material is much more complex than other materials such as steel or concrete, and they are not familiar with the methodology used by geologists during ground exploration (Burland, 1987). Aysen (2005) further claims that *"for a civil engineer the geological history of the soil may not seem to be of much importance as most of the time a civil engineer is searching for a stress-strain model justified by laboratory results"*. Sometimes, besides the naturally occurring soils, the so-called "man-made soils" or "made ground" or "fill" are mentioned as well. The term "man-made soils", among others, encompasses mining spoil and quarry waste. Tailings are usually not specifically listed or described.

Tailings are defined as crushed rock particles that are produced by mineral processing methods, remaining after the recoverable metals or minerals have been extracted from the parent ore. In other words, they represent mining waste deposited afterwards in the slurry form (Vick, 1990). Tailings are produced, depending on the original or naturally occurring rock/ore and the final product/mineral that has to be obtained, usually by several successive procedures. These procedures are held under controlled processing plant conditions and commonly include mechanical methods such as crushing and grinding or comminution, followed by chemical/metallurgical processes such as leaching, flotation or heating (Vick, 1990; Lottermoser, 2010). The final waste material in a slurry form contains mainly fine-grained solid material and waste liquid. Tailings liquids usually contain various process chemicals at elevated concentrations. It is often assumed that tailings solid particles have the same mineralogical composition as the parent rock. However, this is not the case, because physical, chemical and mineralogical properties are changed. Moreover, these properties are changed on purpose within the processing plant, and can change even further at the tailings disposal site over time (Lottermoser, 2010).

Thus, the origin of both materials is the same, i.e. the natural parent rock material, but the nature and duration of the disintegration processes differ considerably (Fig. 2). Natural soil materials have a wide range of particle sizes and their formation is associated with very slow geological processes under complex and variable chemical and physical conditions. Tailings are typically fine-grained materials (the range of particle sizes is much narrower) and represent the final product of mechanical, chemical, and sometimes thermal industrial processing procedures performed rapidly. Moreover, natural soil is transported by gravity, water, wind or glaciers, while tailings are hydraulically transported through pipes, rarely by gravity, more often under certain pressure. Consequently, natural soils and tailings as man-made soils of the same grain-size distribution, characterized by the same testing methods, can exhibit significantly different engineering behaviour.

Although the natural soils and tailings have several things in common, it is worth clarifying their significantly different engineering behaviour to graduated mining/civil engineers. Most of the mining engineering departments contain comprehensive rock mechanics courses, while soil mechanics is covered at an elementary level. At civil engineering departments it is most often exactly the opposite case, i.e. soil mechanics is much more developed than rock mechanics. Man-made soils and especially tailings are almost non-existing within mining and civil engineering curricula at the undergraduate and graduate level. Due to the reasons mentioned in the introduction and the need for the improvement of "tailings engineering" education, the informative graphic shown in Figure 2 is proposed to introduce tailings as man-made materials in comparison to naturally occurring soils, to stress the differences in the nature and rate of their formation, and consequently the differences in their properties and engineering behaviour. The message that should be conveyed is that tailings are not the same material as soil, although by just looking at the soil and tailings samples from the field or grain-size curves they might appear similar. Moreover, further and much more detailed testing becomes necessary to properly characterize tailings materials.

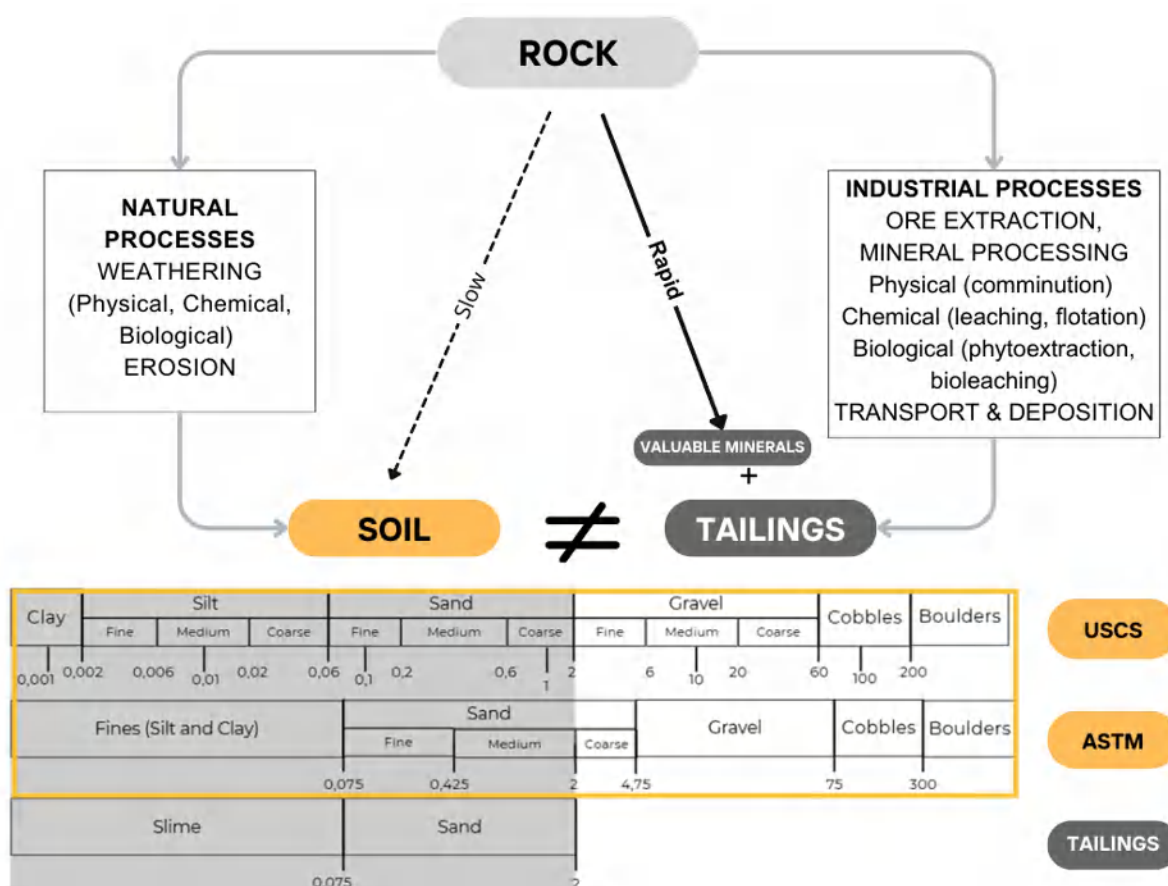


Figure 2. Informative graphic 1: The origin of soils and tailings

8.2 Classification of tailings

The classification of tailings is based on the same testing methods as used for testing of soils, despite the differences related to the origin and engineering behaviour (ICOLD, 2023). Similar to soils, particle size distribution and Atterberg limits are used for the basic characterization of tailings. This can be confusing for students and lead them to wrong conclusions if applied directly without stressing the differences in their origin described in the previous section.

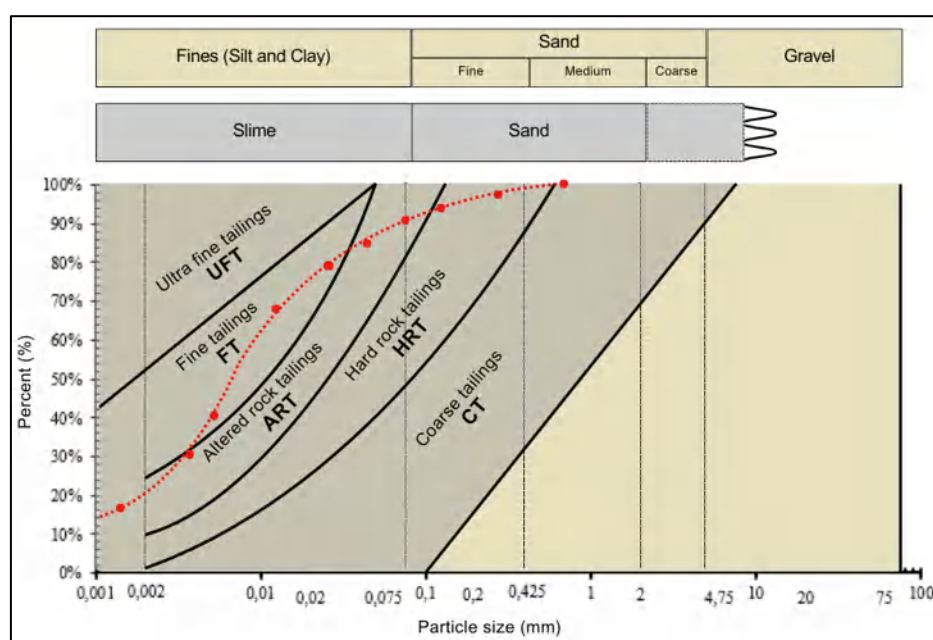
Tailings are traditionally roughly divided into two groups only, i.e. slimes (particles < 75 μm) and sands (particles > 75 μm). The specific terminology used for tailings in "tailings engineering", i.e. slimes and sands, can be misleading to geotechnical engineers. The term slime covers practically the same range as fines according to the ASTM classification, or silt and clay in the USCS. Sands, the other term that refers to tailings, covers the same particle size range as sands in the USCS, but in the ASTM classification system it corresponds to fine to medium sands only. It may also be noted that gravel, cobbles and boulders are excluded from the tailings classification and there is a practical explanation for this. Due to the requirements imposed by processing procedures, all the natural rock materials must be shredded into small sized particles.

According to Bulletin 181 (ICOLD, 2023) tailings are divided into five types: coarse tailings (CT), hard rock tailings (HRT), altered rock tailings (ART), fine tailings (FT) and ultra fine tailings (UFT). It is worth comparing particle size distribution curves and the use of the plasticity chart for tailings and soils (Fig. 3). Most of the tailings belong to the group of fine-grained materials and have similar properties to unconsolidated soils. Four out of five groups of tailings (HRT, ART, FT and UFT) could be classified as fine-grained materials based on the particle size analyses alone. However, this does not automatically imply that tailings possess the plasticity or cohesion properties of soils, which becomes clear from the plasticity chart.

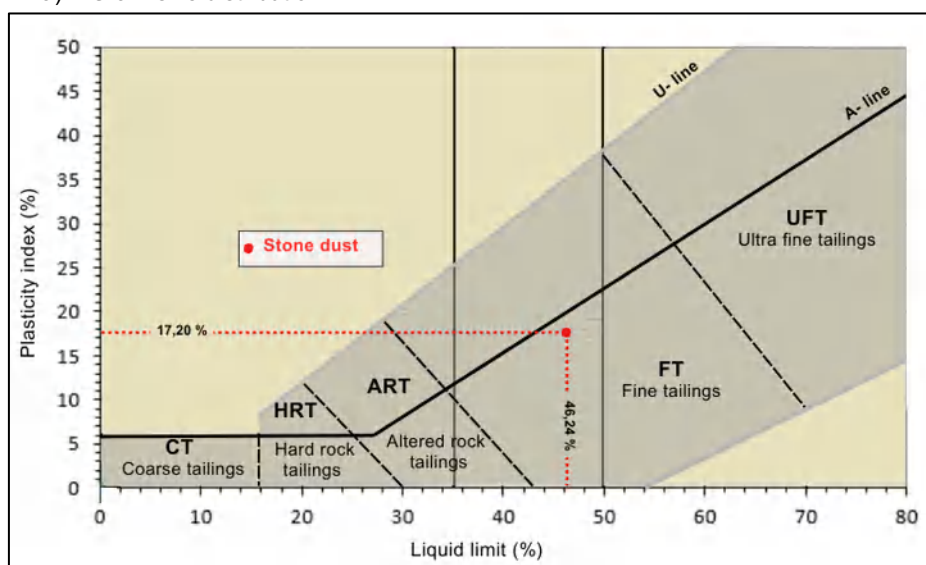
For the comparison of the classification systems used for soils and tailings, the informative graphic shown in Figure 3 could be of use. Tailings grain-size distribution curves can be found in a much

narrower range of particle sizes than those of natural soils. It is even more important to see that plasticity charts used in soil mechanics cannot be followed directly. For the classification of various tailings materials into groups, a different logic must be followed, i.e. A-line does not divide plastic from non-plastic or cohesive from non-cohesive materials.

In conclusion, although both types of materials are tested by the same laboratory methods, the test results should be analysed bearing in mind the origin of the natural and tailings materials. Very often, for the classification of tailings standard procedures used for natural soil materials should be supplemented by additional methods. It would be advisable to perform further mineralogical characterization and X-ray diffraction for tailings that have a higher percentage of clay-size particles to be able to divide “true clay-like” from “rock flour” materials. For example, rock flour can have identical grain-size distribution curves as natural clay material, but it will behave as a non-cohesive material of low plasticity, i.e. exactly the opposite of natural clays. Test results obtained for the pulverized stone from a dimension stone quarry in Croatia are also shown in Figure 3.



a) Grain-size distribution



b) Plasticity chart

Figure 3. Informative graphic 2: Classification of soils and tailings

8.3 Tailings properties

Tailings properties are influenced by their origin (parent ore), mineral processing treatments (physical, chemical, biological) and alteration processes during transportation and deposition into TSFs. Laboratory and in-situ testing methods which are used to obtain physical and mechanical properties of tailings originate from soil mechanics, but testing results can be significantly different. Fourie et al. (2022) elaborated on major differences in the properties of tailings in comparison to natural soils: very large range of specific gravities, much higher in-situ void ratios, tailings particles being mainly angular giving higher friction angles, clay-sized particles of tailings materials not necessarily possessing plasticity and cohesion, etc. Tailings are also characterized by significant volume changes under low effective stresses, highly nonlinear behaviour in compression, and significant reduction of permeability over the range of stresses expected in the field.

It is therefore worth to prepare informative graphics shown in Figure 4 by comparing the typical values of various properties for soils and tailings (Budhu, 2000; Carter & Bentley, 2016; Fourie et al., 2022; Sarsby, 2013; Vick, 1990). Moreover, by additional remarks other relevant issues are stressed, such as the applicability or limitations of certain testing methods, types of testing fluids, etc.

PROPERTIES	SOIL	TAILINGS	REMARK
Total volume	$V = V_s + V_w + V_a$	$V = V_s + V_l + V_g$	Processing liquid/gas
Grain size	0,001 - 60 mm	0,001 - 2 mm	Natural vs. industrial processes
Classification	Gravel >4,75 mm Sand 4,75-0,075 mm Fines (silt, clay) < 0,075 mm	Sand >0,075 mm Slimes <0,075 mm	CT, HRT, ART, FT, UFT additional testings
Particle shape	rounded to angular	angular - very angular	Natural vs. industrial processes
Specific gravity	1,2 - 2,7 organic - unorganic	<1 - >5 coal slimes - metal base slimes	Higher specific gravity results in faster sedimentation
Void ratio	0,3 - 5,0 very dense - organic	0,5 - 11,0 (max. 20-30) fine coal refuse - phosphate slimes	Loose; contractive behaviour
Relative density (D_r)	0 - 100%	30 - 60%	
Plasticity	low - high silt and clay	non-plastic - highly plastic HRT - UFT	Fine tailings can be non-plastic
Permeability	$k = 1 \cdot 10^{-10}$ (m/s) gravel - clay	$k = 10^{-4} - 10^{-10}$ (m/s) coarse sands - highly plastic slimes	Testing fluid; anisotropy; stress and saturation dependency
Compressibility	$C_c = 0,01 - 5,0$ dense gravel - organic	$C_c = 0,05 - 3,0$ copper slimes - phosphate slimes	Highly nonlinear; large strain; oedometer test problematic
Consolidation	$C_v = 0,01 - 5,0$ (m ² /year)	$C_v = 0,05 - 0,35$ (m ² /year)	
Cohesion	cohesive / non-cohesive	mainly non-cohesive	
Shear strength - drained	15 - 40° clay - gravel	22 - 42°	Similar values for slimes and sands due to the angularity of particles; stress dependent
Shear strength - undrained	$s_u / \sigma_v' = 0,1 - 1,0$	$s_u / \sigma_v' = 0,15 - 0,40$	Similar to soft, NC soils

Figure 4. Informative graphic 3: Soil vs. tailings properties

There is another important issue to be considered. The sampling of tailings is extremely difficult, and together with the spatial and temporal variability of materials within TSFs, there may be considerable uncertainty in obtaining design properties. The use of in-situ testing methods is burdened by other problems, such as the use of correlations derived from the data on other types of materials, i.e. mainly naturally occurring soils and not tailings.

Concluding remarks

The inverted TSFs triangle is proposed following the conceptual Burland's geotechnical triangle to be used either in practical engineering or for the development of curricula or specific courses related to the mine waste or TSF management. To fulfil the demands of the mining industry and the recently developed standards, recommendations or even regulations, the designers, the site-based staff and others included in TSF management regardless of their background (mining engineering/civil engineering/other) are expected to possess comprehensive knowledge of all the aspects shown in the inverted TSFs triangle.

Unfortunately, due to a lack of interest for engineering study programs globally, especially in the fields of mining and mining geotechnics, the shortage of highly specialized tailings engineers is expected to be also high. Therefore, it is the responsibility of higher education institutions to find ways on how to attract younger generations in such a challenging sector and to offer adequate teaching materials and programs from the graduate level upwards.

Tailings materials resemble natural soils most closely. Therefore, as a good starting point, the focus is given to the soil mechanics syllabus analyses with the intention to offer introductory teaching materials to give an insight into the peculiarities of tailings engineering. From the list of topics covered by basic or introductory soil mechanics courses offered at mining/civil engineering programs, introductory lectures on the origin, characterization and classification were chosen. The comparison is made for soil and tailings materials, and informative graphics are prepared to show how some well-established concepts and theories from soil mechanics engineering should be challenged and critically examined if applied to tailings. The next step would be to conduct a survey among the students enrolled in the geotechnical engineering and mining geotechnics programs at the graduate level to assess whether the teaching materials offered have initiated interest for tailings engineering. If so, similar materials are planned to be developed for all topics at the intersection of soil mechanics and tailings engineering, such as field testing (use of remote surveying technologies, advanced digital terrain analysis), water flow and seepage (comparison of calculations with the assumption of isotropic versus anisotropic permeability), sedimentation and consolidation (testing and modelling), shear strength (volumetric behaviour in shear, static liquefaction), slope stability (brittle or ductile behaviour), construction and placement of materials (compaction, cycloning), monitoring and surveillance (harsh environments, robust equipment, timeframe).

References

- Aysen, A. (2005). *Soil Mechanics: Basic Concepts and Engineering Applications*. A.A. Balkema, London, UK.
- Azam, S., Li, Q. (2010). Tailings Dam Failures: A Review of the Last One Hundred Years. *Geotechnical News*, 28, pp. 50-53.
- Budhu, M. (2000). *Soil Mechanics and Foundations*. John Wiley & Sons, Inc., New York, USA.
- Burland, J. B. (1987). Kevin Nash Lecture. The teaching of soil mechanics – a personal view. *Proceedings of the 9th European Conference on Soil Mechanics and Foundation Engineering*, Dublin, vol. 3, pp. 1427–1447.
- Burland, J. B. (2012). The geotechnical triangle. In: Burland, J., Chapman, T.; Skinner, H., Brown, M. (Eds.) *ICE Manual of Geotechnical Engineering, Volume I: Geotechnical Engineering Principles, Problematic Soils and Site Investigation*. ICE Publishing, London, UK, pp. 17-26.
- Carter, M., Bentley, S. P. (2016). *Soil Properties and their Correlations*, second ed. John Wiley & Sons, Ltd, Chichester, UK.
- Davies, M. (2002). Tailings Impoundment Failures: Are Geotechnical Engineers Listening? *Waste Geotechnics*, 20, pp. 1-36.
- Fourie, A., Verdugo, R., Bjelkevik, A., Torres-Cruz, L. A., Znidarcic, D. (2022). Geotechnics of mine tailings: a 2022 State of the Art. *Proceedings of the 20th ICSMGE*, Rahman and Jaksa (Eds), pp. 121-183, Australian Geomechanics Society, Sydney, Australia.

- GTR (2020). Global Industry Standard on Tailings Management. https://globaltailingsreview.org/wp-content/uploads/2020/08/global-industry-standard_EN.pdf
- ICOLD (2001). Tailings Dams – Risk of Dangerous Occurrences, Lessons Learnt from Practical Experiences, Bulletin 121.
- ICOLD (2023). Tailings Dam Design: Technology Update, Bulletin 181. CRC Press/Balkema, Leiden, The Netherlands.
- Leonida, C. (2020). Tailings engineers wanted. E&MJ Engineering and Mining Journal, 221(11), pp. 22-27.
- Lottermoser, B. G. (2010). Mine Wastes: Characterization, Treatment and Environmental Impacts, third ed. Springer, Berlin, Germany.
- Rana, N.M., Ghahramani, N., Evans, S.G., McDougall, S., Small, A., Take, W.A. (2021). Catastrophic Mass Flows Resulting from Tailings Impoundment Failures. Engineering Geology. 292, 106262. <https://doi.org/10.1016/j.enggeo.2021.106262>.
- Sarsby, R.W. (2013). Tailings dams. In: Environmental Geotechnics, 2nd edition. ICE Publishing, London, UK.
- Spencer, L., Hatton, C., Bareither, C., Ward, K., Scalia, J. (2021). Deck Hands Needed! Experience Necessary – Addressing the Impending Qualified Tailings Professional Resource Shortage. Proceedings of the 2021 Mine Waste and Tailings Conference. Brisbane, Australia.
- Stark, T., Moya, L., Lin, J. (2022). Rates and Causes of Tailings Dam Failures. Advances in Civil Engineering. 2022(4), pp. 1-21. DOI: 10.1155/2022/7895880.
- Vick, S. G. (1990). Planning, Design, and Analysis of Tailings Dams. BiTech Publishers Ltd, Vancouver, B.C. Canada.

Authors' bios

Biljana Kovacevic Zelic, University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering (Croatia)

Dr. Biljana Kovacevic Zelic is a professor at the University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Croatia, who specialises in the field of mining geotechnical engineering. She graduated in mining engineering from the University of Zagreb, Croatia, and obtained an M.Sc. and a Ph.D. at the same university. Her main areas of interest are geotechnical and geoenvironmental engineering, soil mechanics, testing and application of bentonites. She holds E-learning Management and E-learning Course Design certificates. She is a member of ISSMGE TC306 Geoengineering Education and SOMP Society of Mining Professors Educational committee. She was the Vice-dean for education (2005-2009) and the Dean of the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb (2009-2013). She has published more than ten papers related to higher education, curriculum development and quality control of HEIs.

Mirela Burecic Safran, Zagreb University of Applied Sciences (Croatia)

Mirela Burecic Safran is an assistant at the Zagreb University of Applied Sciences, Civil Engineering Department, where she participates in delivering of several courses: Soil Mechanics, Geotechnics, and Contemporary Methods in Geotechnics. She earned her master's degree in mining engineering from the University of Zagreb, Faculty of Mining, Geology, and Petroleum Engineering, and is currently a doctoral student at the same faculty. Her main areas of interest include soil mechanics, geotechnical engineering and numerical methods in geotechnics.

Dobroslav Znidarcic, University of Colorado, Boulder (USA)

Dr. Znidarcic is an Emeritus Professor in the Department of Civil, Environmental, and Architectural Engineering at the University of Colorado at Boulder. He has over 50 years of professional experience as a researcher, an educator and a consultant. He has developed novel testing techniques for determining consolidation properties for mine tailings and other soft soils that are today routinely used in engineering practice throughout the world, especially in the mining industry and dredging operations. He also developed comprehensive numerical models for predicting field behaviour of soft mine tailings and dredged spoils after deposition and throughout the drying process. His other research and teaching interests include embankment dam and levee design and stability evaluations, unsaturated soil behaviour and use of centrifuge modelling in research and education.

Simplifying slope stability: What should be taught at the undergraduate level?

C.J. MacRobert

Stellenbosch University, Stellenbosch, South Africa
macrobert@macrobert.com

ABSTRACT: Theoretical methods available for analysing slope stability have advanced significantly in recent years. Undergraduate educators are faced with the dilemma of determining what to teach. Despite these advances, an accurate understanding of soil layers and pore pressure conditions remains. This paper reviews common topics presented at the undergraduate level before focusing on the authors teaching practices. Teaching starts with affective case studies before an active learning activity is used to help students develop a conceptual understanding of key factors influencing slope stability. Initially, simple non-technical terms are encouraged but these are latter mapped to correct technical terms. Constraint theoretical models (for vertical cuttings, infinite slips and undrained rotational failures) are then presented and applied to the case studies initially presented. General theoretical models (for drained failures) are presented last and applied to case studies. Teaching prioritises developing conceptual understanding and using simple methods to analyse actual case studies.

Keywords: Slope stability, Curricula choices, Active learning, Simple methods, Conceptual understanding

1 Beyond theoretical analysis

When introducing slope stability in their classic textbook Terzaghi & Peck (1967) stated, "Because of the extraordinary variety of factors and processes that may lead to slides, the conditions for the stability of slopes usually defy theoretical analysis." This statement must be kept in mind when reading this paper as simple calculations will be advocated for teaching slope stability to undergraduates. The Terzaghi & Peck (1967) quote highlights how minor discontinuities and variations in stratigraphy must be modelled for theory to match observation. Often these variations cannot be captured in simple models.

So, what should be taught at the undergraduate level? To understand key aspects to be taught a review of seven readily available undergraduate textbooks was undertaken. The review considered both theoretical approaches (Table 1) and general concepts that should be taught (Table 2). Cataloguing theoretical approaches was less subjective compared to cataloguing general concepts. A more thorough review may show that the general concepts listed are covered elsewhere in respective texts, however, this review only catalogued them if they were covered in slope stability sections or chapters.

Theoretical approaches included limit analysis, limit equilibrium and chart-based methods. Limit equilibrium methods for infinite slopes and rotational slides were common. No texts present the friction circle method (see Lambe & Whitman (1969)). Approaches presented are all amenable to hand calculation, which may seem quaint considering modern limit equilibrium methods (Lam & Fredlund, 1993), discontinuity layout optimization (Smith & Gilbert, 2007, Sloan, 2013) and finite element methods (Griffiths & Lane, 1999). However, presenting these complex methods at an undergraduate level is unlikely wise considering the cognitive load and time available.

Most textbooks present these theoretical methods from first principles. While derivation and application of these equations can help students visualise driving and resisting actions; lectures and assessments

can get bogged down in trigonometric identities and algebraic acrobatics. It is then questionable whether the blizzard of equations gives students a conceptual grasp of whether a particular slope with given strength is stable. Chart-based methods could be argued to provide a means for students to visually see how changes in key parameters (slope angle, slope height, strength parameters) impact stability. However, the use of charts is now rare in practice questioning their continued inclusion in instruction.

Table 1. Theoretical approaches covered in common English language Geotechnical Engineering textbooks

Content	Textbooks
Limit analysis applied to:	
• Vertical cuttings	1,3
Limit equilibrium applied to:	
• Vertical cuttings	1,3
• Wedge failures	4,7
• Infinite slopes	
○ Undrained soil ($\phi = 0$)	3
○ Dry slope	2,3,4,5,6,7
○ Downward seepage	2,5
○ Parallel seepage	1,2,3,4,5,6,7
• Rotational slips	
○ Undrained soil ($\phi = 0$)	1,2,3,4,6,7
○ Method of slices ($\phi \neq 0$)	
○ Fellenius/Swedish method	1,2,3,4,5,7
○ Bishop method	1,2,3,4,5,7
○ Janbu method	2
Chart based methods:	
• Slurry supported excavations	1
• Rotational slips in undrained soils ($\phi = 0$)	1,2,3,4,6,7
• Rotational slips in drained soils ($\phi \neq 0$)	3,4,6
• Rotational slips in drained soils ($\phi \neq 0$) with steady -state seepage	4,7
• Rotational slips with earthquake forces	4
1. Craig's soil mechanics by Knappett & Craig (2020) 2. Soil mechanics: Concepts and applications by Powrie (2014) 3. An introduction to the mechanics of soils and foundations by Atkinson (2007) 4. Fundamentals of geotechnical engineering by Das (2008) 5. Soil mechanics: A one-dimensional introduction by Muir Wood (2009) 6. Geotechnical engineering: A practical problem solving approach by Sivakugan & Das (2010) 7. Smith's elements of soil mechanics by Smith (2014)	

General concepts (Table 2) included categorisation of slope failures, factors affecting shear strength, accounting for uncertainty in design and remedial measures. Categorisations of slope failures were not as comprehensive as those found in geology focused textbook such as *Geology for engineers and environmental scientists* by Kehew (2006). Considering the earlier Terzaghi & Peck (1967) quote, it could be argued that more emphasis should be placed on describing and categorising slope failures. However, making decisions on using nature for the convenience of man, requires civil engineers to go beyond simply describing what they see to making calculated predictions of future states. This requires theoretical models and accounting for uncertainty. Considering the importance of remedial measures in practice it is surprising how little this topic is covered in undergraduate textbooks. No doubt, coverage of retaining structures goes some way to addressing remedial measures.

Table 2: General concepts covered in common English language Geotechnical Engineering textbooks

Content	Textbooks
General discussion (specific sections within text on slope stability):	
• Types of instability	1,3,6,7
• Behaviour of simple beach/laboratory scale sand excavations	3,5
• Stress changes in slopes	3
• Influence of water on stability	3
• Definition of factor of safety	4,6
• Choice of strength parameters and factor of safety	3
• Designing to Eurocode 7	7
• General methods of slices and need for computers	1,3,6
• End of construction and long-term stability	1
• Embankments and earth dams	1
• Rapid drawdown	1,7
• Laterally loaded piles for slope stabilisation	2
1. Craig's soil mechanics by Knappett & Craig (2020)	
2. Soil mechanics: Concepts and applications by Powrie (2014)	
3. An introduction to the mechanics of soils and foundations by Atkinson (2007)	
4. Fundamentals of geotechnical engineering by Das (2008)	
5. Soil mechanics: A one-dimensional introduction by Muir Wood (2009)	
6. Geotechnical engineering: A practical problem solving approach by Sivakugan & Das (2010)	
7. Smith's elements of soil mechanics by Smith (2014)	

This review was undertaken whilst deciding on content to teach to undergraduate civil engineering students at Stellenbosch University. Craig's soil mechanics by Knappett & Craig (2020) has been the prescribed textbook for several years and content choices are broadly aligned. Teaching is a dynamic process, and different methods have been used over time. This paper documents methods considered, methods developed, reasons for choosing certain methods and rejecting others. Hopefully, these examples will provide food for thought as you develop your own teaching practices.

2 Taking it outside

Civil engineering students at Stellenbosch University complete three modules in Geotechnical Engineering over their four-year degree program. The first module presents fundamental geology and engineering geology (over 9 weeks), the second focuses on basic soil mechanics (over 12 weeks) and the third focuses on applied geotechnical engineering (over 12 weeks). The first two modules are presented sequentially in the second year and the third module is in the third year. Slope stability is presented in the third module building on earlier knowledge of shear strength and seepage.

For slope stability, contact time is limited to six lectures (50 minutes each) and 2 tutorials (3 hours each) giving a total contact time of 12:40 hours. This is split equally over two weeks. Students are expected to spend roughly the same amount of time on self-study. Unstructured surveys (e.g., Positive, Negative and Improvement (PNI) feedback and informal discussion) have shown students spend too little time on self-study. Consequently, effort is made to include activities that help students structure their self-study. This takes teaching outside of contact sessions and hopefully helps create lifelong learners.

Activities include low stakes reading quizzes, podcasts and providing tutorial questions early. Low stakes reading quizzes (true/false) require students to read through relevant textbook sections ahead of lectures. Weekly 12-minute podcasts provide biographical sketches of key geotechnical engineers from South Africa. One covers Dereck Sparks and Gerhard Heymann who developed slope stability analysis methods and another covers Fredrich Bell and Rodney Maud who mapped landslide hazards. Tutorial questions are provided early so students can attempt them prior to formal tutorial sessions.

3 More than semantics

Curricula and methodological choices were guided by the semantic dimension of Legitimation Code Theory (LCT) as outlined by Maton (2013). The semantic dimension is defined by semantic density and semantic gravity. Semantic density refers to the technical precision of language used, whereas semantic gravity pertains to how dependent meaning is to a particular context.

Low semantic density uses simple and imprecise language to describe something, whereas high semantic density uses specific terminology. While technical terms associated with high semantic density may be easy for experts to understand, novices will initially find these difficult and will need scaffolding to map these dense terms to more basic terms with low semantic density they are familiar with.

Where meaning is closely linked to a specific example, meaning is said to have strong semantic gravity. If meaning is context-free or abstract, then meaning is said to have weak semantic gravity. It is often useful to introduce a concept with strong semantic gravity as there is a concrete context that students can relate to. However, if meaning is limited to a specific example, students may fail to see how the concept is more generally applied. Teachers must complete the cycle by generalising meaning with weak semantic gravity.

Maton (2013) advocates that teaching follows a ‘Semantic Wave’ which is both a progression and an oscillation between weaker and stronger semantic gravity and density. Figure 1 is a high-level overview of activities used to teach slope stability. Instruction begins by presenting real-world case studies (strong semantic gravity and low semantic density), next an intuitive slope stability exercise is used to develop a conceptual slope stability framework (weak semantic gravity and low semantic density), teaching progresses to derivations for specific types of failures (strong semantic gravity and high semantic density) and ends with deriving generic equations (weak semantic gravity and high semantic density). While there is an overall progression through the quadrants, there is also an oscillation between other quadrants (e.g., a derived equation is applied to an earlier case-study) to maintain the semantic wave.

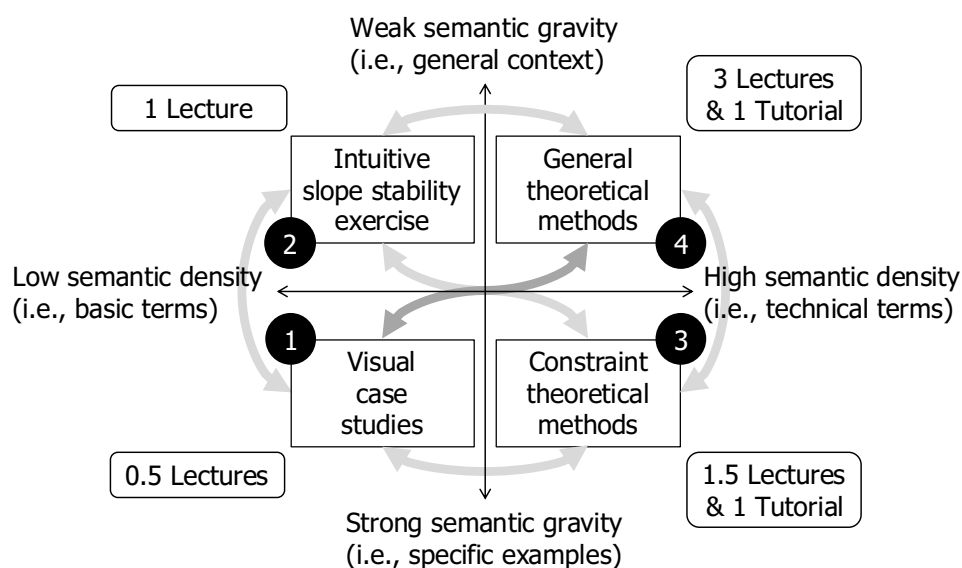


Figure 1. Semantic plane illustrating semantic wave used in teaching slope stability

In addition to being guided by the semantic dimension of LCT, pedagogical choices were made to favour active learning. Active learning is any course work that students perform that is not simply watching, listening and taking notes (Felder & Brent, 2016). Sometimes, active learning is defined as activities implemented during traditional lecture periods (Silverthorn, 2006), however, a broader definition including activities done outside the classroom (Prince, 2004) is adopted here. Active learning is favoured as it has been shown to outperform traditional lecturing in various measures of learning outcomes (Prince, 2004).

4 Visual case studies

Slope stability is introduced by means of case studies presented with low semantic density and strong semantic gravity. Case studies are initially used for affective purposes, to excite and motivate students, later they are used for cognitive purposes to illustrate, develop and apply theoretical methods. The following factors, informed by Orr & Pantazidou (2012), guided the choice of case studies:

- Simple: Slope failures can have disputed mechanisms or be a consequence of multiple factors (Duncan et al., 2014). For instance, while the Brumadinho tailings dam failure is dramatic its failure mechanism is disputed limiting its use in teaching (see Robertson et al., (2019), Wates (2024), Zhu et al., (2024)). Dramatic failures are important to highlight the risk associated with engineering decision making, nevertheless, simple case studies are needed to illustrate methods actually taught (Poulos, 1998). Case studies by early geotechnical pioneers (e.g., A. Skempton, L Bjerrum, H. Golder, H. Ireland and R. Peck) are often suitable in this regard.
- Known: While mainly qualitative information is required when using case studies for affective purposes, enough background information should be known to be taken off-script by students. Quantitative detail is required when using case studies for cognitive purposes. This can limit case studies to those taken from the lecturer's professional practice. Slopes often become case studies after a failure; invariably as details were overlooked or there was a lack of data. Thus, details are often sparse, and students need to appreciate this ambiguity (Poulos, 1998).
- Local: Case studies with strong semantic gravity are those closest to a student's context. Maintaining a good relationship with local practitioners is helpful in obtaining local case studies. Invariably some important case studies will not be common in the local geology and case studies from further afield will need to be sought.

Five types of case studies are used in teaching at Stellenbosch University. First are dramatic slope failures to illustrate failure consequences. Examples include a failed road embankment (Figure 2a), unravelling of a concrete faced rockfill dam (CFRD) during construction following unprecedented rainfall (Figure 2b) and the Brumadinho tailings dam failure (videos from YouTube).

Second are vertical cuttings to emphasise the danger of unsupported excavations to counter the apparent safety implied by theoretical methods (Wesley, 2012). Examples include test pits excavated by local consultants (Figure 2c) and videos posted by the Trenching and Excavation Safety Taskforce (TEST).

Third are infinite slopes. Stellenbosch University is geographically surrounded by mountains where infinite slip failures following prolonged rainfall are common (Figure 2d). Infinite slips associated with end-tipped sand residues from mining along the West Coast of South Africa (Figure 2e) are also useful.

Fourth are rotational failures modelled with undrained strengths. To reduce ambiguity soil strength is treated as either undrained ($\tau = c_u$ with $\phi = 0$) or drained ($\tau = \sigma' \tan \phi$ with $c' = 0$). Particularly useful here are case studies of causeways, stockpiles or trial-embankments on clays (Figure 2f) as they are amenable to hand calculation. Several examples can be found in the literature (e.g., Skempton & Golder (1948), Yong & Ting (1984)).

Fifth are case studies modelled with drained strengths. Figure 2g shows a rotational failure of a reservoir cutting caused by blocked drains and Figure 2h shows the installation of a liner for an industrial waste facility for which translational failure was important. Examples in the literature can be found but often need simplification (e.g., Skempton (1964), Seed et al., (1990)).



a. Road Failure



b. CFRD Unravelling

Figure 2. Photographs of case studies



Figure 2. (continued). Photographs of case studies

5 Intuitive slope stability exercise

Engineers need a sense for whether a structure is safe or within acceptable proportions (Petroski, 1985, Vick, 2002). Students often show a poor grasp of how slope geometry and soil strength impact stability. To address this a computer-based exercise wherein students visually progressed through 150 slopes with different geometries and strengths was developed for use prior to lectures on slope stability. Slope scenarios were presented sequentially and students asked to predict whether each was stable or not before each solution was presented. While this activity gave students an intuitive sense of stability on par with practising engineers (MacRobert, 2018) it required too much student time (4 hours of self-study time and 2 hours of contact time) and frequent reprogramming to justify its continued use.

As the need for an intuitive feel remained the exercise was reconfigured. The reconfigured exercise is paper-based and requires students to work in groups of four. Groups are given 48 slope stability scenarios with different heights (5 or 10 m), slope angles (90, 45, 34, 27 or 18°) and strength parameters (undrained, drained with a phreatic surface or drained without a phreatic surface). Figure 3 shows three examples of how the 48 slope stability scenarios are presented, included are a verbal descriptor of consistency, strength parameters, phreatic surface (if present), slope height, slope angle, critical slip circle and the factor of safety. Using the 48 scenarios, groups spend 25-minutes developing language or symbolic heuristics to describe how different variables influence stability. After this the 48 slope scenarios are returned, and students use the developed heuristics to order five new scenarios (without the critical slip surface or factor of safety shown) from most stable to least stable within 5-minutes.

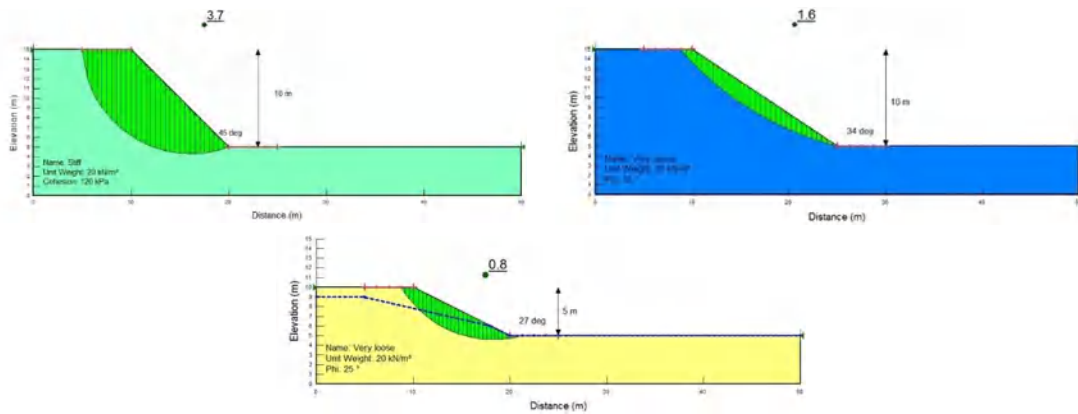


Figure 3. Examples of slope stability scenarios

Figure 4 shows developed heuristics have low semantic density and different levels of accuracy. Over the three years the exercise has run only 7 of the 40 groups have ordered all the new sets correctly with 19 of the 40 groups ordering at least three correctly. No clear correlation between heuristic accuracy and performance has emerged. However, the verbal descriptors of consistency (e.g., medium dense) appear to have a greater influence than a comparison between strength parameters and slope geometry. The next exercise iteration will test this hypothesis to improve future iterations. After the exercise is complete, examples of good heuristics are displayed as a basis for a ± 15 -minute discussion to reinforce key factors with high semantic density.

- a.
- The higher the cohesion factor, the higher SF; more stable
 - The smaller the slope angle, the higher the SF; more stable
 - If it has a water table, The SF is lower; less stable
 - The denser the soil, the higher the SF is; more stable
 - The increase in height; decrease in SF (less stable)
 - If the slope angle decreases, the failure area increases
- Heuristics:
- ① Bigger angle and bigger height, shorter seepage (safer)
 - ② For same - steeper one is less safe
 - b. ③ For 90° - height influence safety
 - ④ Bigger angle - unsafe (time dependent) (some FOS)
 - ⑤ More dense - more catastrophic failure (unsafe)
- cohesion must be same

Figure 4. Examples of heuristics developed: a. Clear and concise, and b. Confused and conflicting

6 Constraint theoretical methods

Three constraint theoretical models are presented in the high semantic density and strong semantic gravity quadrant. These are equations to determine the stability of undrained vertical cuttings, drained infinite slopes and undrained rotational slides. Equations for vertical cuttings are derived using the limit analysis approach (see Knappett & Craig (2020) for derivations). The general upper bound equation is derived and critical heights for different mechanism inclinations calculated and plotted as an active learning exercise to illustrate how the mechanism is minimised. The lower bound is then used to confirm the correct mechanism has been found. Emphasis is placed on the temporal nature of the stability apparent from these equations. Lecturers with more time may wish to present relationships for slurry supported excavations as this is a practical way to excavate vertically (see Knappett & Craig (2020)).

The temporal stability of vertical cuttings becomes apparent with the introduction of equations for drained infinite slopes. Two derivations are common, the first assumes parallel seepage at a depth proportional to the slip height (see Knappett & Craig (2020)) and the second assumes seepage over the entire slip

height but at different inclinations (see Powrie (2014)). The second derivation is presented, and students use this in an active learning exercise to illustrate how seepage rotation driven by infiltration causes an initially stable slope to fail (Figure 5a). Vertical cutting and infinite slope equations can be used together as a strong semantic gravity illustration of beach excavation stability (see Atkinson (2007)).

Rotational failures defined with undrained strengths clearly illustrate driving and resisting moments. In Figure 5b the driving moment is expressed as a point load that increases with embankment height (the moment due to the clay self-weight cancels out) and the resisting moment is generated by the undrained shear strength mobilised over the slip circle (assuming a tension crack forms in the embankment). Groups of students calculate the factor of safety for different heights and plot a graph to determine the critical embankment height. The main tutorial questions are then calculating the factor of safety for a simple slope, then estimating how the factor of safety changes with a house on the crest (a point load), and then if there is an earthquake (generating a horizontal moment). Progressing through these three theoretical methods (vertical cutting, infinite slope, and undrained rotational slip) gradually decreases semantic gravity and prepares students for the more general theoretical methods presented next.

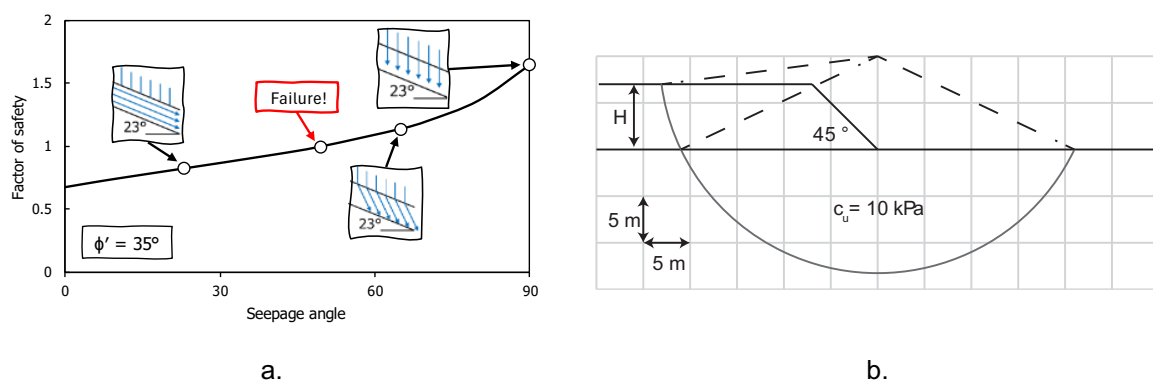


Figure 5. Constraint theoretical models: a. Rotating seepage, and b. Trial embankment on clay

7 General theoretical methods

The method of slices is introduced in the second week with high semantic density and weak semantic gravity. It is pointed out to students, that the need for slices is because the drained strength criterion requires the determination of normal effective stresses acting along the circle (even though the normal effective stresses have no moment). After sketching a free body diagram of a slice on the board, students identify the forces acting on the slice. Considering this together with the number of equations available reveals the problem to be indeterminate. This requires making assumptions to make the problem determinate.

Two assumptions about interslice forces are used to show how the problem can be made determinate. The first is the Swedish method which assumes zero resultant interslice forces and the second is the Bishop method which assumes the vertical interslice force resultants are zero but non-zero in the horizontal direction. As students struggle with this concept both a graphical explanation (Figure 6) and a mathematical derivation (see Sivakugan & Das (2010)) are used to develop respective equations.

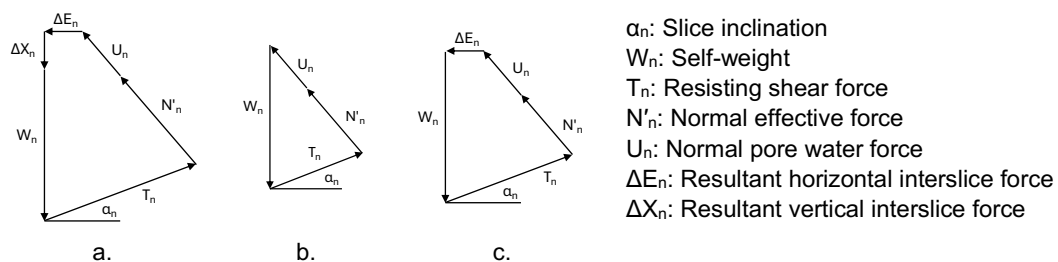


Figure 6. Method of sSlices: a. Force polygon for n th slice, b. Swedish method, and c. Bishop method

The two methods are illustrated by applying them to the forensic analysis of the rotational failure of the reservoir (see Figure 2g and Figure 7a) assuming the reservoir is empty. The Swedish method is used to estimate the friction angle that would result in the dam failing (Figure 7b). The Bishop method is then used to show that with the lower phreatic surface and the back-calculated friction angle the factor of safety is 1.3. The lecture then segue ways to a discussion of safety and dealing with uncertainty in design. This can be done by either discussing acceptable factors of safety (Working Load Design) or partial factors (Limit State Design). In this case partial factors are used consistently across all sections of the module (i.e., also for foundation and retaining walls) and simplified so students do not get confused as to which partial factor to use (i.e., two design approaches are used across all problems).

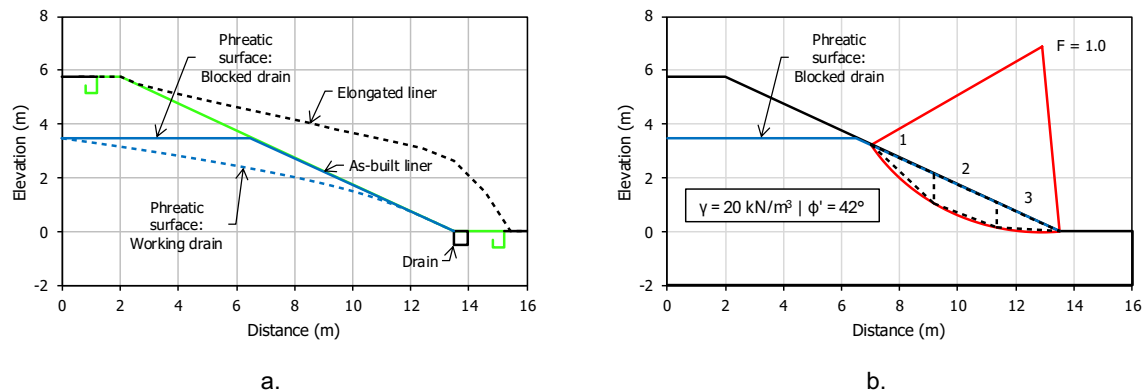


Figure 7. Rotational failure of reservoir: a. Detailed cross-section, and b. Swedish method cross-section

Tutorial questions require evaluating whether a given slope meets a stated design approach, determining friction angles to reduce the factor of safety to unity, and calculating the factor of safety for a slope. Both circular and non-circular translational failures are presented with a maximum of five slices. Some questions require determining all geometric properties (slice inclinations, slice widths, slice weights, and pore pressure heads) but most questions (and all summative assessments) include partially completed tables with geometrical properties. Questions thus focus on applying methods.

8 Final points

Lectures on slope stability conclude with a discussion (± 10 -minute) on more rigorous limit equilibrium methods used in practice and that multiple slip surfaces must be evaluated to determine the critical slip surface. Both these aspects necessitate the use of software. The need to search for the critical slip surface is easy to visually illustrate using a series of strategically chosen slope stability outputs. While much can be said about searching for critical slip surfaces; emphasis at this level is placed on pointing out that critical undrained slip surfaces are often deep seated; whereas critical drained slip surfaces are shallow, unless there is a low strength layer or an elevated water table. Understanding the magnitude of a potential failure is important in quantifying the associated risk. Finally, emphasis is continuously placed on the need to accurately characterise the soil layers present and estimating the pore pressures as these are significantly more important than any calculation undertaken.

References

- Atkinson, J. (2007). The mechanics of soils and foundations, second ed. Oxon, Taylor & Francis.
- Das, B. (2008). Fundamentals of geotechnical engineering, third ed. Ontario, Canada, Thomson Learning.
- Duncan, J., Wright, S. and Brandon, T. (2014). Soil strength and slope stability, second ed. John Wiley & Sons.
- Felder, R., Brent R. (2016). Teaching and learning STEM, first ed. San Francisco, Jossey-Bass.
- Griffiths, D., Lane, P. (1999). Slope stability analysis by finite elements. *Géotechnique* 49(3), pp. 387-403.

- Kehew, A. (2006). *Geology for engineers & environmental scientists*, third ed. New Jersey, Pearson Prentice Hall.
- Knappett, J., Craig, R. (2020). *Craig's soil mechanics*, ninth ed. Oxon, Spon Press.
- Lam, L., Fredlund, D. (1993). A general limit equilibrium model for three-dimensional slope stability analysis. *Canadian Geotechnical Journal* 30(6), pp. 905-919.
- Lambe, T., Whitman, R. (1969). *Soil mechanics*, first ed. John Wiley and Sons.
- MacRobert, C. (2018). Introducing engineering judgment through active learning. *Journal of Professional Issues in Engineering Education and Practice* 144(4), pp. 05018009.
- Maton, K. (2013). Making semantic waves: A key to cumulative knowledge-building. *Linguistics and Education* 24(1), pp. 8-22.
- Orr, T., Pantazidou, M. (2012). Use of case studies in geotechnical courses: Learning outcomes and suitable cases. *Shaking the Foundations of Geo-engineering Education*. McCabe, Pantazidou and Philips. Galway, Ireland, Taylor & Francis, pp. 105-110.
- Petroski, H. (1985). *To engineer is human*. New York, Vintage Books.
- Poulos, H. (1998). Theme lecture: Geotechnical education towards 2000. 14th International Conference on Soil Mechanics and Foundation Engineering, Hamburg, Germany, pp. 2565-2572
- Powrie, W. (2014). *Soil mechanics: Concepts and applications*, third ed. Boca Raton, CRC Press.
- Prince, M. (2004). Does active learning work? A review of the research. *Journal of Engineering Education* 93(3), pp. 223-231.
- Robertson, P., de Melo, L., Williams, D., Ward Wilson, G. (2019). Report of the Expert Panel on the Technical Causes of the Failure of Feijão Dam I.
- Seed, R., Mitchell, J., Seed, H. (1990). Kettleman Hills waste landfill slope failure. II: Stability analyses. *Journal of Geotechnical Engineering* 116(4), pp. 669-690.
- Silverthorn, D. (2006). Teaching and learning in the interactive classroom. *Advances in Physiology Education* 30(4), pp. 135-140.
- Sivakugan, N., Das, B. (2010). *Geotechnical engineering: A practical problem solving approach*, first ed. Fort Lauderdale, J. Ross Publishing, Inc.
- Skempton, A. (1964). Long-term stability of clay slopes. *Géotechnique* 14(2), pp. 77-102.
- Skempton, A., Golder, H. (1948). Practical examples of the $\phi = 0$ analysis of stability of clays. 2nd International Conference on Soil Mechanics and Foundation Engineering. Rotterdam.
- Sloan, S. (2013). Geotechnical stability analysis. *Géotechnique* 63(7), pp. 531.
- Smith, C., Gilbert, M. (2007). Application of discontinuity layout optimization to plane plasticity problems. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 463(2086), pp. 2461-2484.
- Smith, I. (2014). *Smith's Elements of Soil Mechanics*, ninth ed. West Sussex, John Wiley and Sons
- Terzaghi, K. and Peck, R. (1967). *Soil mechanics in engineering practice*, second ed. New York, Wiley.
- Vick, S. (2002). *Degrees of belief: Subjective probability and engineering judgment*. Reston, Virginia, ASCE Publications.
- Wates, J. (2024). Application of bursting pressure and conventional drained behavioural theory to the Brumadinho failure. *Journal of the South African Institution of Civil Engineering* 66(3), pp. 29-36.
- Wesley, L. (2012). Rethinking aspects of theory and tradition in soil mechanics teaching. *Shaking the Foundations of Geo-engineering Education*. McCabe, Pantazidou and Philips, Taylor & Francis, pp. 83-89.
- Muir Wood, D. (2009). *Soil Mechanics: A One-Dimensional Introduction*, first ed. Cambridge, Cambridge University Press.
- Yong, K., Ting, S. (1984). Slip failure of embankment on soft marine Clay. 1st Conference of the International Conference on Case Histories in Geotechnical Engineering, University of Missouri—Rolla, pp. 1079-1082.
- Zhu, F., Zhang, W., Puzrin, A. (2024). The slip surface mechanism of delayed failure of the Brumadinho tailings dam in 2019. *Communications Earth & Environment* 5(1), pp. 1-13

Author's bio

Charles J. MacRobert, Stellenbosch University (South Africa)

Charles John MacRobert is an Associate Professor of Geotechnical Engineering in the Department of Civil Engineering at Stellenbosch University. His education saw him spend time at both the University of Cape Town and University of the Witwatersrand. Research focuses include improving geotechnical design thinking by considering case studies, forensic analysis of failures and participant observation. Specialised consulting is provided for characterisation and modelling of geomaterials for global stability and seepage assessments. This emphasis on practice enables him to confidently teach the professional art of engineering.

Developing parallel MSc / Degree Apprenticeship pathways in Geotechnical Engineering

A. Monzer, D.V.L Hunt, I. Jefferson & A. Royal

Dept. of Civil Engineering, University of Birmingham, Birmingham, UK

a.monzer@bham.ac.uk, d.hunt@bham.ac.uk, i.jefferson@bham.ac.uk, a.c.royal@bham.ac.uk

ABSTRACT: As global infrastructure projects expand, the demand for geotechnical engineers continues to rise. A Master's (MSc) degree provides specialised knowledge, facilitating career progression in geotechnical engineering. With the introduction of Level 7 Degree Apprenticeships (DAs) in the UK, growing evidence suggests this pathway offers a viable alternative to traditional MSc programmes, driven by increasing industry demand. This paper examines the redevelopment of an existing MSc into parallel MSc/Level 7 DA programmes, establishing a robust UK standard through industry-academia collaboration. The programmes will produce graduates with core competencies in knowledge, skills, and behaviours aligned with the industry's requirements, better preparing them for local and global challenges. A comprehensive review of module delivery, assessment, and integration led to significant improvements in content delivery and a more interactive learning environment. The revised structure challenges students with real-world geotechnical scenarios while fostering stronger industry partnerships that drive ongoing innovation and flexibility. Key enhancements include greater use of ICT tools, industry-driven curriculum design, and flexible learning approaches. This approach ensures that graduates are equipped with practical skills and ready to contribute effectively from day one. The success of the MSc/DA programmes demonstrates the importance of continuous collaboration between academia and industry in shaping future geotechnical professionals. These changes have been widely embraced by students and employers, reinforcing the value of integrating academic rigour with hands-on experience.

Keywords: *Geotechnical engineering, Postgraduate education, Degree Apprenticeship (DA), Industry-academia partnership*

1 Introduction

The primary goal of this paper is to present the transformation of the traditional MSc programme in Geotechnical Engineering, using the example of the MSc/Level 7 Degree Apprenticeship Standard and associated programmes developed in the UK. This transformation was not only a response to current and future industry needs, exemplifying how robust industry-academia partnerships can shape modern educational approaches, whilst attracting the best students for the future of the geotechnical engineering sector (Kajastie, 2025). This is not a new issue as Marcuson et al. (1991) demonstrated when discussing how to attract better students into the geotechnical engineering profession. The integrated approach is designed to address challenges in geotechnical engineering education, providing a scheme that could be adapted by other institutions seeking to prepare their graduates for complex, real-world challenges, now and in the future.

1.1 Background context

The United Nations (United Nations, 2018) estimates that (at the time) "55% of the world's population lives in urban environments and this is expected to increase to 68% by 2050"; potentially resulting in "an estimated additional 2.5 billion people living in the urban setting, much of this taking place in Africa and

Asia". Hence, in today's rapidly evolving world, global population growth and increasing urbanisation have led to rising demands on infrastructure, such as roads and rail networks, energy generation and transmission, water (treated and waste), telecommunications, tunnels, and housing. The associated increase in demand for housing and suitable infrastructure, with continued urbanisation, highlights the crucial demand for specialist engineers who can design, build, and manage these systems which form the foundations of modern society. Clearly geotechnical engineering is at the heart of these processes, underpinning many key infrastructure development and maintenance, for example (and not limited to) the sector is crucial for: power generation facilities and transmission networks including the development of offshore wind farms; water treatment, storage and distribution; tunnels and other underground-space usage; and of course transportation networks, all of which are vital to the UK's success/growth.

The need for growth is underpinned by the UK Government's recent statement (UK Government, 2025a) on planning reform for growth and housing, which place significant importance on infrastructure and increasing the Country's housing stock. Hence geotechnical engineering is a vital contributor to the sustainable and resilient growth and maintenance of these assets, both in the short and long term. Furthermore, Government initiatives, such as Invest 2035: The UK's Modern Industrial Strategy (Reynolds, 2024), stress the importance of a highly skilled workforce, especially as domestic talent shortages persist (Department for Digital, Culture, Media & Sport, 2022). Rising overseas recruitment costs further highlight the need for innovative training models as a strategic solution (Halfon, 2023) to attract more people into the industry. For instance, during the National Apprenticeship Week 2023, the theme "Skills for Life," highlighted the importance of fostering a diverse and skilled workforce, underscoring the role universities can play in strengthening partnerships with employers to tackle future skills challenges; it also emphasised prioritising apprentices, and their development, throughout the process (National Apprenticeship Week, 2023). This was recently highlighted by the Institute for Apprenticeships and Technical Education (soon to be Skills England) (Institute for Apprenticeships and Technical Education, 2021) following a survey of over 30 geotechnical managers/engineers concluding the importance of employer/educator partnerships and the benefits such collaboration brings to students and employers alike. Earlier, Jaksa et al. (2009) provided a comprehensive overview of key facets of geotechnical engineering education and training, highlighting the critical role of industry engagement in shaping knowledge and skills, for the future.

Unfortunately, this profession (geotechnics) is considered a shortage occupation and without suitable ways to attract people into the industry, and train them appropriately, it could potentially impact on a country's growth and prosperity; the ability of the profession to attract a diverse talent pool, noting that in the UK for example, only 20% of the workforce in the profession are women and only 8% identifying as Black, Asian, or minority ethnic (Ground Engineering, 2023), with these figures significantly below UK population averages. In addition, increasing diversity in the sector fosters greater creativity and innovation. Furthermore, the GE100 2021 industry survey by Ground Engineering (Kajastie, 2021) underscored the growing shortage of qualified professionals, significantly impacting both the sector and those dependent on geotechnical services. To address this challenge, changes in recruitment and training practices for geotechnical engineers are essential.

1.2 Postgraduate education of geotechnical engineers: the traditional postgraduate taught degrees and the new degree apprenticeship

A purist might argue that geotechnical engineering is a discipline within Civil Engineering and should only be practiced by those with a background in Civil Engineering. However, the reality in industry (based on interactions with industry and industry bodies) does not appear to conform to this stance. geotechnical engineering is a profession that is in shortage (as noted previously) and industry will draw not only from civil engineering but also those who have backgrounds outside of engineering, including those with backgrounds in geology or related disciplines such as engineering geology, earth sciences, geophysics and mining/quarrying.

In the UK, Geotechnics is traditionally introduced at the Undergraduate (UG) level in civil engineering (and associated variations) degrees (e.g. BEng and MEng) or as a specialist Master's level postgraduate programme (e.g. MSc, diplomas or certificates). Geotechnical engineering (or limited aspects of it) might be introduced in some UG geology (or associated variations) degrees but this might be considered relatively unusual, hence those entering the profession from these backgrounds would likely require postgraduate training to practice in the industry. For nearly 70 years (at the time of writing), the University of Birmingham has been a leader in geotechnical engineering education in the UK with its MSc degree

programme. Over time, the MSc programme was redesigned to better accommodate part-time students, meet the growing demand for geotechnical engineering training among geologists, and incorporate valuable feedback from the industry. These redesigns were iterative, continuously enhancing the programme to ensure they remained relevant to the industry. For approximately the past two decades, the programme has specialised in training diverse cohorts of full-time and part-time students, including those with and without engineering backgrounds.

Master's level Degree Apprenticeships (DAs) (level 7 – Master level education) were launched by the Government in 2015. Degree apprenticeships vary from normal degree programmes in that they are developed by industry, in conjunction with the Institute for Apprenticeships and Technical Education, and result in the creation of a Degree Apprenticeship Standard. The Standard sets out the requirements for the apprenticeship to ensure those who pass the apprenticeship have the competency to practice. The Standard defines the core competencies required, which are broken down into three categories: Knowledge, Skills and Behaviours (KSBs), and any degree programme developed to deliver the apprenticeship must introduce the KSBs within the taught materials/sessions. The completion requirements for Level 7 Apprenticeships exceed those of a standard Master's degree programme as apprentices must not only successfully complete a Master's level degree but also provide evidence demonstrating how all KSBs are implemented into their professional practice. Additionally, they must pass a final assessment that is separate from, and in addition to, the Master's degree assessments (known as the End Point Assessment). DAs are funded through the Apprenticeship Levy (UK Government, 2025b), a tax imposed on companies with a wage bill that exceeds a stated threshold, and companies have the right to claim back their levy contribution to train their employees via apprenticeships (including the cost of the degree). If the levy is not (fully) claimed by those taxed, then other companies can apply to the levy to train their employees via apprenticeships, including Small and Medium Enterprises (SMEs) (UK Government, 2025c). When undertaking DA training, the company is committing to undertake the apprenticeship training “in-house”; the apprentice is provided a mentor (e.g. a line manager or experienced colleague) to supervise them and help provide the required experiences so that the apprentice can implement all the stated KSBs in their professional practice (and produce evidence of this for the apprenticeship – usually a requirement to pass the programme). Apprentices are also allocated to an academic tutor and the apprentice, tutor and mentor are required to regularly hold review meetings regarding the progress of the apprenticeship. These meetings can include consideration of performance on the taught programme, consideration of short-term objectives to develop evidence for KSB implementation in work, etc., and are designed to help support the apprentice during their apprenticeship. Employers not only provide mentors to help their apprentices develop the KSBs but also provide them with time within their working life to focus upon their apprenticeship. This is known as off-the-job training, and allows the apprentice to develop/implement their KSBs whilst in work. The academic component of the DA is undertaken within the University setting and contributes to the off-the-job training of the apprentice. Hence, the philosophy underpinning the DA is very different to the traditional Master's level training approach; whilst the academic content might be the same, the apprentices are mentored in-work and are actively given opportunities to develop their KSBs in their working lives, whilst undertaking a degree, before completing their end point assessment.

Prior to the introduction of any DA there is a requirement of industry (in collaboration with academia) to develop a DA standard. Hence, in 2019, a meeting with industry and academic representatives was held to consider the development of a Degree Apprenticeship Standard for Geotechnical Engineering. This meeting was successful, and it led to the development of the Level 7 Degree Apprenticeship Standard in Geotechnical Engineering. This was approved for delivery in 2021 and is available on the Institute for Apprenticeships and Technical Education website (Institute for Apprenticeships and Technical Education, 2021). The launch of the Geotechnical Engineering Standard resulted in the reformulation of the Geotechnical Engineering MSc programme to facilitate the introduction of the Geotechnical Engineering DA as a parallel programme at the University of Birmingham; this was driven by the need to create an educational model that responds to modern industry requirements and challenges. This approach was particularly important given that many participants come from non-engineering backgrounds, including geology and environmental sciences. Furthermore, entry requirements for a DA, as outlined in the Standard, are not necessarily the same as those associated with a traditional MSc; by design this is a way of encouraging more people into higher education, not least those who might not normally consider such an approach thereby encouraging social mobility. Offering the DA as a credible alternative pathway to the traditional MSc route, the University of Birmingham (other training partners are available) has expanded opportunities for professional growth

while promoting social mobility. Degree apprenticeships also present a valuable opportunity to enhance workforce diversity (Ground Engineering, 2023). Notably, at Birmingham, approximately 50% of the current apprentices across cohorts in this DA programme (at the time of writing) are women.

1.3 The degree apprenticeship, an alternative philosophy to training geotechnical engineers

Higher education is considered essential to equip those entering geotechnical engineering with the specialised competencies required to practice and innovate within this field. DAs provide a viable alternative to traditional MSc programmes, helping to address the critical skills gap in geotechnical engineering by attracting those into the industry who might not have normally considered this profession as a career. Employers are placing increasing value on these DA programmes, with specialist organisations (such as the Federation of Piling Specialists) championing their use to attract people into the industry (Chick, 2020). The integrated approach associated with DAs develops both theoretical understanding and practical competencies as the apprentices undertake their apprenticeship. It can be argued that this is also true for those undertaking the MSc as part-time students whilst practising in the industry; the key difference being that in the apprenticeship route, the employer commits to provide their apprentices with the required experiences to meet all KSBs listed in the Apprenticeship Standard, giving a far rounder experience, whereas this might not be the case on the MSc.

The core competencies within the Geotechnical Engineering DA Standard, coupled with the roles of the apprentices/part-time students who have joined the programmes since its launch in 2022, indicate that geotechnical engineering does not denote a single, narrowly focused role. Instead, the occupation encompasses a spectrum of roles: from engineering geologists to civil engineers; from ground investigation to construction specialists, designers to asset managers; and those acting as intermediaries between other engineering and earth sciences specialisations that interact with geotechnical engineering but are not geotechnical practitioners themselves. This diversity is essential for the industry's success but presents unique challenges when delivering Master's level education. Given the diverse nature of cohorts undertaking an MSc or DA in Geotechnical Engineering, great care must be taken to develop a programme that meets the needs of the industry, students, and accrediting bodies, among other stakeholders.

2 Redevelopment of the MSc/DA programmes

2.1 Driven by industry for industry

The University of Birmingham's MSc in Geotechnical Engineering, at the time of writing, has been running for nearly 70 years, boasts strong employability rates, a positive reputation in industry and receives positive feedback from those graduating. However, to ignore drivers for change, such as the launch of the DA, would almost ensure the programme becomes stagnant and irrelevant, doomed to close. To maintain relevance, a comprehensive needs analysis would be undertaken periodically, between representatives from the University's Geotechnical Engineering Research Group and industrial stakeholders, to consider the programme with both academic and professional demands. A recent example of this was the participation in, and implementation of the outcomes from, an in-depth focus on the industry's needs with the development of the Degree Apprenticeship in Geotechnical Engineering.

In 2019, an exploratory meeting with over thirty representatives from ground investigation companies, contractors, consultants, utility and infrastructure owners/operators, professional bodies, and academia laid the groundwork for developing the Level 7 Degree Apprenticeship (DA) Standard in Geotechnical Engineering. This required the formation of an industrial trailblazer group, under the guidance of the Institute for Apprenticeships, to consider current needs, and possible future trends, to develop the DA Standard. This was an involved process, taking over two years to complete; once finished the group had identified the core competencies (expressed as KSBs) that every Master's-level geotechnical engineer should possess, ensuring the apprentices graduate with the practical expertise required in the field. This collaborative process culminated in Government approval in 2021 (Institute for Apprenticeships and Technical Education, 2021), with the University of Birmingham offering the apprenticeship for the first time in 2022 (other provider(s) are also available).

The approval of the Geotechnical Engineering DA Standard could have resulted in the replacement of the existing geotechnical engineering provision at the University with the DA, although this was not the outcome chosen. Instead, a new iteration of the MSc, aligned with the DA, was developed so that both the traditional MSc and the new DA pathway could be offered in parallel; the programmes can be undertaken as a full-time or part-time MSc student, or part-time apprentice, providing more choice to students. Each pathway offers the blend of academic sessions and practical applications traditionally associated with the programmes at Birmingham and each encompasses the core competencies outlined in the DA Standard. Regardless of the chosen pathway, graduates gain exposure to the essential themes sought by industry. The main difference in programmes is that the apprentices are provided opportunities to implement these competencies into their professional practice by their employer (Jefferson et al., 2022) so they can develop the evidence required for the final DA assessment; this is not required in the traditional MSc pathway.

2.2 Key steps in redevelopment

Developing the new DA pathway and updating the MSc was challenging; cohorts include those with engineering backgrounds and those without; some are full-time whilst others as part-time; some are confident in mathematics and comfortable with teaching via mathematical argument, others are more observational or kinaesthetic in their learning; hence the range of needs can be considerable. Balancing the needs of these groups was a significant challenge and should not be underestimated. Equally, robust support mechanisms are essential for those who require assistance or lack confidence in their abilities, particularly individuals returning to education after a prolonged absence. Finally, the requirements of industry (as outlined in the apprenticeship standard), were extensive (encompassing over 40 KSBs) and must be covered within the pathways. This could necessitate long-periods of lectures, potentially limiting opportunities for group work, tutorials, and guest lectures; factors that are crucial to the overall learning experience. Modules are taught via intensive week-long lecture periods and previous experience indicates that lecture-heavy content throughout this week is not as effective to student learning as a more mixed approach, which incorporates worked examples and tutorial sessions, along with guest lecture sessions and group-activity case studies with the lectures. To meet the requirements of the DA Standard, and provide a balanced and effective teaching environment, some form of prioritisation was required for the KSBs (e.g. which might be introduced in one module but run across several modules, allowing for knowledge stacking). When deciding how to prioritise competencies (e.g. engineering behaviour of soil against contract appreciation or teamwork) during curriculum design, recommendations from the DA's industrial partners were drawn on; a weighted focus of competencies was recommended, prioritising things like engineering aspects of soil behaviour, ground investigation, analytical and numeric approaches to consider geotechnical interventions, over teamwork and communication, contracts and health and safety. This is not to say that any of the KSBs were removed from the programme, all are present, but that certain ones were given more prominence within the taught component of the degree pathways. To parody George Orwell "All KSBs are equal, some are more equal than others". This approach provided a balanced structure across the modules, with some competencies emphasised throughout the programme and others concentrated in specific modules (University of Birmingham, 2025).

The Covid-19 pandemic was disruptive to teaching and during this period hybrid methods, not used previously on the programme, were developed to allow for teaching during periods of social-distancing and lockdowns. Lessons learned from this period were incorporated into the redevelopment of the MSc/DA programmes to help address challenges associated with the diverse backgrounds of the cohorts. This involved the creation of materials hosted on a virtual learning environment, which were released prior to teaching, including worked examples and interactive quizzes, as well as pre-recorded materials. Students can access these in advance of the taught materials and refer to them later, at their convenience. With these materials accessible in advance, less time is required for formal lecturing and more time can therefore be focused on key topics, worked examples, group-case studies, etc. Building on this approach, the hybrid teaching model provided flexibility and fostered a dynamic learning environment, allowing students with diverse backgrounds to benefit from each other's knowledge. At the same time, core materials remained readily accessible at the click of a button.

To further support the diverse cohort, the programme structure was designed to build-in complexity over time. Pre-reading materials are issued prior to the start of the course, introducing core engineering and mathematical concepts to ensure foundational understanding; these form the basis for a pre-programme

refresher course in mathematics and mechanics to ensure that all students are adequately prepared. These refresher sessions are undertaken at the pace of the class and are developed to build confidence in knowledge and skills that might not have been used for quite some time. These sessions include examples taken from the programmes themselves to indicate what is required and what, with practice, is achievable. Mathematical techniques were integrated throughout the curriculum, rather than taught separately (after the pre-programme refresher), with regular practice through work examples and tutorials, helping students build confidence and mastery. The hybrid model also allowed for responsive teaching, enabling lecturers to adapt lesson plans based on students' progress and focus on areas of difficulty. Initial modules introduce the fundamentals, subsequent modules build on these and start to introduce uncertainties and complexities associated with engineering practice, and the final module offers a team-based challenge based on a loosely defined brief and poorly defined materials (but with time dedicated in the laboratory for the groups to experiment and develop their ideas); this necessitates the drawing on experiences from previous modules to complete the challenge successfully. Following the completion of the taught materials, the students undertake an individual research project which mandates they apply the higher levels of thinking (using Bloom's Taxonomy as a guide: Cardiff Metropolitan University, 2024).

2.3 Educational strategies

The overarching pedagogical principles followed the constructivist principles of learning developed in the 20th century, with experienced learners providing scaffolded learning environments for novice learners in the field. This was applied to both the electronic resources in the virtual learning environment and in the lecture room or practical class. Educational strategies within the lecture room were developed using Rosenshine's principles of instruction, which include building on prior knowledge, breaking down complex topics into manageable components, and incorporating practical examples to contextualise theory (Rosenhine, 2012). Worked examples built in complexity and follow the I-We-You approach, applying the theory to problems and providing the students/apprentices with a controlled space where these techniques could be practised and misconceptions identified and addressed. These principles facilitated student engagement through examples, independent practice, and routine feedback provided (real-time in class, via online quizzes, via assessment, etc.) to reinforce learning.

The MSc and DA pathways provided structured progression, with full-time students and apprentices following a set route and part-time students offered flexibility through a suggested path. The curriculum is presented in self-contained modules; these initially focus on fundamentals (soil mechanics, soil-structure analysis, etc) before introducing applied engineering practices (e.g. earthworks, long-term asset management, ground investigation and problematic ground conditions, etc). Subsequent modules draw on the lessons from previous ones and build on them, applying the theory to more complex, or uncertain situations. To facilitate this, the programmes once again draw on support from industrial representatives who give case-study based sessions and/or set the students/apprentices real-world challenges to consider and develop suggested solutions (before the industrialists present their solutions).

Complexity and uncertainty are also built into the assessments, to provide the students with experience of real-world applications in a controlled environment; although the level of uncertainty is not constant, it increases during the course, to allow the students to develop their abilities and competencies over time. To facilitate this, assessments draw upon a library of case-studies very kindly provided by industrialists who support the programmes.

Continued professional development (CPD) is fundamental to life-long learning and professional practice and this is core to both programmes. A professional geotechnical society hosts evening lectures at the University repeatedly throughout the year and all those on the programmes are invited to attend. Part-time students might live too far away to make these practicable, in these instances they are encouraged to attend local group activities or online events hosted by the Institution of Civil Engineering, Geology Society or other learned, and related institutions (University of Birmingham, 2025). The importance of CPD is recognised in the DA as it forms one of the competencies, hence it is required that the apprentice demonstrates their commitment to CPD in their work.

The final two components (complexity and uncertainty, and CPD) were deliberately introduced into the programmes to develop transferable skills that the students could draw on throughout their careers. Fostering resilience, self-reliance and the ability to identify unknowns and propose solutions, is important as it is clearly impossible to teach all a student will need for the next 40 years, or so, of professional

practice. For example, forty years ago, the internet was not the readily available resource of information it is today, hence concepts such as Construction 4.0, BIM, digital twins, and the practical use of Artificial Intelligence were either unheard of or unavailable; the evolution of communication technology has enabled multinational projects and international engineering teams to thrive. Who can predict what the next 40 years will bring? However, the development of these domain specific skills, which can be transferred to new scenarios within the profession, will provide students/apprentices with the skills to practice in an ever-changing and uncertain world.

3 Outcomes and impact

3.1 Benefits for students

The parallel MSc/DA programmes have had/are having a profound impact on their students, equipping them with industry-mandated competencies that make them highly attractive to employers. Graduates acquire both theoretical knowledge and practical expertise, equipping them for senior roles in geotechnical engineering. The DA, driven by industry demand, demonstrates how this pathway fosters diverse talent development, providing apprentices with hands-on experience while progressing towards chartership (Ground Engineering, 2023). Since its launch in 2022, feedback from programme participants has been positive, examples of which are given below:

Charlotte, Engineering Geologist ... “I recently completed the MSc Geotechnical Engineering course at the University of Birmingham having studied part-time over 3 years while working as an Engineering Geologist. The course provides a balance between theoretical understanding and real-world application of a range of subject areas within geotechnics. The knowledge gained from each module rapidly proved invaluable as it provided me with a greater understanding of the work I was undertaking in industry. As a part-time student the self-contained module block format was excellent. I was able to focus fully on the module material in a condensed manner which helped with learning but also reduced disruption to my job. The structure also offers a good balance between formal lectures and self-directed study and the course staff are available to provide help and support so you can reach your potential. Considering this, and the direct application within industry, I would recommend the course to anyone thinking about a career in geotechnical engineering.”

Rebecca, Engineering Geologist ... “I was encouraged to join the DA course by my former colleagues who were already on the course and were finding it helpful for their roles. I was a little hesitant at first, but I knew that the course could give me a firm foundation on which to build my geotechnical skills and help me to progress into more technical areas. It has been a steep learning curve, but it is definitely helping to plug the gaps in my knowledge. During the course I was unfortunately made redundant, but the university was very supportive, and I believe being part of DA was attractive to prospective employers. The transition from one company to another was seamless with no disruptions to my learning.”

Tom, working in ground investigation ... “The Geotechnical Engineering MSc offered by the University of Birmingham is a high-quality course and I’d recommend the degree apprentice route as a first point of call for any professionals looking to advance their career. As a ground investigation contractor, I’ve found the block release programme to be the most manageable and it’s ensured I have the time I need to focus on my learning. Owing to the apprenticeship being a joint venture with your employer, I’ve also found it helps attract more opportunities within work to help advance my career as a geotechnical engineer, delivering much greater value as a result.”

3.2 Advantages for industry

The benefits for the industry are equally compelling, with employers widely embracing the Degree Apprenticeship (DA) model. Funded through the Apprenticeship Levy, the DA eliminates tuition fees for apprentices, making it a financially viable alternative to traditional MSc programmes. This is particularly advantageous for Small and Medium-sized Enterprises (SMEs), where the high cost of MSc programmes can be prohibitive. Beyond financial benefits, the modular structure of the programme allows companies to schedule training around work commitments, with apprentices attending campus for approximately 8 to 9 days per module. Employers have reported significant improvements in

students' competencies and practical skills after module completion. Below are examples of feedback from employers:

David, Technical Director and Training Manager, Card Geotechnics Limited (CGL) ... "CGL have been delighted to collaborate with Birmingham University with our Early Career (EC) staff enrolled on the degree Apprenticeship in Geotechnical Engineering. We currently have 4 staff attending across 3 years of the programme. The delivery model has been easy to manage in terms of staff resourcing and the academic content has fully meshed with our expectations. Participation has proven to be well contested with EC staff keen to undertake this course as part of their long-term career development."

Tom, Geotechnical Design Team Leader, Amey Limited ... "Here at Amey, we see the provision of the 'Geotechnical Degree Apprenticeship Level 7' as a fundamental part of the ongoing and future development of the Geotechnical profession in the UK. Given the current economic climate, the availability of such a comprehensive training scheme that equips students with the right practical knowledge and skills cannot be understated. This apprenticeship programme not only provides immense value to the students but also the associated employers, and by extension, the wider industry."

Richard, Assurance Director of an SME in the Rail/Civil Engineering sector ... "As a smaller sized SME, we have always attempted to develop our staff but have at times found it cost and time prohibitive when it comes to higher education. The degree apprenticeship route has helped facilitate executing this development in an affordable manner that has not impacted too greatly on time. This has benefited the company with a knowledgeable competent professional employee and thus projects a good image to our clients'."

Paul, Managing Director of PJS Consulting Engineers ... "The degree apprenticeship programme has allowed PJS to upskill team members without losing them to full-time university study. This approach blends workplace experience with academic learning, shaping apprentices into well-rounded engineers. With the government's plans to expand the UK's infrastructure and targets for building 1.5 million homes, significant growth in Geotechnical and Geo-environmental engineering is anticipated, making this the ideal time to strengthen our team. Government funding for these programmes has alleviated the financial strain of training costs. As a small business, degree apprenticeships have supported our organic growth, with apprentices now making up 35% of our team. It is evident that degree apprenticeships, and levy funding, has a crucial role to play in enabling the government to achieve its objectives for the delivery of infrastructure, housing, and SME growth."

These testimonials underscore the impact and success of the MSc/DA programmes, demonstrating their alignment with industry expectations and their value to students, employers, and the broader geotechnical sector.

4 Challenges and model transferability

4.1 Implementation challenges

Transitioning from a traditional MSc programme to the parallel MSc/DA programmes structure presented several challenges. Ensuring the curriculum was: both challenging and relevant; modules were not overpopulated with materials; materials were accessible for the diverse cohorts; and incorporating complexity, uncertainty and CPD, to help develop transferable skills required to practice now and into the future; required careful planning, continuous adjustments, and extensive engagement with stakeholders. Implementing the transitioning was problematic due to existing part-time students who had signed on to the previous iteration of the MSc programme and were at various stages of completion. These students required bespoke pathways to ensure that they could successfully complete their degrees and that the proposed pathways for these individuals still met the requirements of the programme's accrediting body so that the completed programme could be used as part of a professional recognition application (chartership). The new programmes equally faced initial complications (as happens with the launch of all new programmes) although the students taking them were generally forgiving and remained very positive about the overarching qualities of the programme. This good-will was developed through open and transparent communications between parties, with interventions applied quickly to address the identified issues. Once these complications were dealt with the programmes continue to run smoothly, although future complications are almost a certainty, and these will be dealt with in the same manner.

The programmes include robust feedback processes (both formal and informal), facilitating regular communication between students, academics and industry representatives. Feedback ensures that the curriculum remains adaptable and responsive to relevant developments and (as noted above) allows for rapid action if things go awry. The collaborative structure, which included joint committees of academic staff and industry professionals, proved invaluable in effectively managing the challenges faced during the implementation of the new programmes.

4.2 Transferability of the model

The success of the University of Birmingham's MSc/DA Geotechnical Engineering programmes highlights its adaptability and potential for broader application. While apprenticeship training in the UK is a devolved matter; the DA Standard, overseen by the Institute for Apprenticeships and Technical Education (Institute for Apprenticeships and Technical Education, 2021), applies only in England, the framework's core competencies are publicly accessible. This allows institutions in Scotland, Northern Ireland, Wales, or those overseas to tailor the approach to their specific needs.

DAs have successfully bridged the gap between education and industry by providing experience in-house training alongside academic qualifications. To ensure their continued growth, universities, employers, and the government must collaborate on regulatory reforms, SME engagement, and widening participation to address workforce demands and skills shortages (Wade, 2024). That said, DAs are not a direct replacement for traditional degrees and should instead be seen as another alternative that broadens choice for the training of geotechnical engineers.

5 Concluding remarks

The redevelopment of the traditional MSc programme into parallel MSc/Level 7 Degree Apprenticeship University Master's programmes has been shown to produce significant benefits and offers an alternative pathway (the DA route) to traditional postgraduate provision (the MSc route). The strong collaboration between academia and industry has been central to this success, ensuring that the curriculum remains highly relevant and programmes popular with industry. Moreover, the DA approach appears to have broadened participation, bringing a diverse range of students into the discipline.

Based on the experiences gained developing these parallel pathways, institutions looking to develop similar programs should engage early and often with industry partners, ensure that the curriculum meets the needs of the programme (in this case both fully align with DA Standard) and understand the implications of what is required (if undertaking a DA the requirements are extensive and specific) from the outset. Establishing robust feedback mechanisms is also essential for ensuring that such programmes continue to meet both academic and industry standards/requirements over time and complications can be dealt with in a timely manner.

The parallel MSc/Level 7 Degree Apprenticeship programmes provide robust pathways for modern geotechnical engineering education. By integrating academic study with case studies and, for those on the DA or part-time MSc pathways incorporating real-world geotechnical experiences gained in industry, these programmes enhance learning by providing practical context. They address critical skills shortages, support lifelong learning, and foster a diverse, innovative workforce equipped to tackle present and future challenges. Through collaboration between the geotechnical engineering sector and academic institutions, these initiatives contribute to building a resilient and forward-thinking workforce for the future.

Acknowledgements

The launch/redevelopment of the geotechnical engineering programmes (MSc and DA) at the University of Birmingham would not have been possible without many people, who practice within the industry, being prepared to give up their time and provide their expertise during this process and we are very grateful to all involved for this support and express our gratitude.

In addition, the geotechnical engineering programmes would not be so successful without continued support from industry, with representatives supporting our programmes by not only providing continued feedback and advice on the content/focus/direction of the programmes but also giving up their time to

come and present to the students/apprentices. This is very much appreciated and once again we express our gratitude to all involved.

Finally, whilst four authors are listed on this paper, the members of the Geotechnical Research Group within the University are all active, in various capacities, within the support and delivery of the MSc/DA provision and we would like to express our gratitude to our colleagues for all their support.

References

- Cardiff Metropolitan University (2024). Taxonomy of learning. Retrieved from: https://library.cardiffmet.ac.uk/learning/learning_theories/taxonomy
- Chick, J. (2020). Apprenticeship Degree in Geotechnical Engineering (Level 7). FPS. Retrieved from: <https://www.fps.org.uk/news-views/news/apprenticeship-degree-in-geotechnical-engineering-level-7/>
- Department for Digital, Culture, Media & Sport (2022). DCMS Sectors Skills Shortages and Skills Gaps 2019. Department for Digital, Culture, Media & Sport. Retrieved from: <https://www.gov.uk/government/statistics/dcms-sectors-skills-shortages-and-skills-gaps-2019>
- Ground Engineering (2023). Geotechnical industry embraces degree apprenticeship route. Ground Engineering. Retrieved from: <https://www.geplus.co.uk/opinion/geotechnical-industry-embraces-degree-apprenticeship-route-15-05-2023/>
- Halfon, R. (2023). How We Are Supporting Degree Apprenticeships and Higher Technical Education. Retrieved from: <https://www.gov.uk/government/speeches/how-we-are-supporting-degree-apprenticeships-and-higher-technical-education>
- Institute for Apprenticeships and Technical Education (2021). Geotechnical Engineer – Level 7 Apprenticeship Standard. Retrieved from: <https://www.instituteforapprenticeships.org/apprenticeship-standards/st0881-v1-0>
- Jaksa, M.B., Ho, K.K.S. & Woodward, M.A. (2009). Management, training and education in geotechnical engineering. Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering, Alexandria, Egypt, 3136 – 3170.
- Jefferson, I., Royal, A., Hunt, D. (2022). Post National Apprenticeship Week – some reflections from a Level 7 Degree Apprenticeship provider. Retrieved from: <https://www.birmingham.ac.uk/schools/engineering/civil-engineering/postgraduate/level-7-apprenticeship-reflections>
- Kajastie, N. (2021). GE100 2021: Skills time bomb. Ground Engineering. Retrieved from: <https://www.geplus.co.uk/features/ge100-2021-skills-time-bomb-17-09-2021/>
- Kajastie, N. (2025). Future-proofing engineering talent. Ground Engineering March 2025, 28-34. Ground Engineering. Retrieved from: <https://www.geplus.co.uk/features/future-proofing-engineering-talent-through-apprenticeships-14-02-2025/>
- Marcuson III, W.F., Dobry, R., Nelson, J.D., Woods, R.D., Loud, T.L. (1991). Issues in Geotechnical Engineering Education, Journal of Professional Issues in Engineering Education and Practice, 117 (1), 1-9.
- National Apprenticeship Week. (2023). National Apprenticeship Week 2023: skills for life. Retrieved from: <https://naw.appawards.co.uk/>
- Reynolds, J. (2024). Invest 2035: the UK's modern industrial strategy. Department for Business and Trade. Retrieved from: <https://www.gov.uk/government/consultations/invest-2035-the-uks-modern-industrial-strategy>
- Rosenshine, B. (2012). Principles of instruction: Research-based strategies that all teachers should know. American Educator, 36(1), p.12.

UK Government (2025a). Government goes further and faster on planning reform in bid for growth. Retrieved from: www.gov.uk/government/news/government-goes-further-and-faster-on-planning-reform-in-bid-for-growth

UK Government (2025b). Guidance: Pay Apprenticeship Levy. Retrieved from: www.gov.uk/guidance/pay-apprenticeship-levy

UK Government (2025c). Guidance: Apprenticeship Funding. Retrieved from: www.gov.uk/government/publications/apprenticeship-funding/apprenticeship-funding

United Nations (2018). News: 68% of the world population projected to live in urban areas by 2050, says UN. Department of Economic and Social Affairs. Retrieved from: www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html#:~:text=Today%2C%2055%25%20of%20the%20world's%20population%20lives%20in,is%20expected%20to%20increase%20to%2068%25%20by%202050

University of Birmingham (2025). Geotechnical Engineering Level 7 Degree Apprenticeship. Retrieved from: <https://www.birmingham.ac.uk/study/postgraduate/subjects/civil-engineering-courses/geotechnical-engineering-apprenticeship>

Wade, G. (2024). 10 ways we can boost degree apprenticeships. Universities UK. Retrieved from <https://www.universitiesuk.ac.uk/what-we-do/policy-and-research/publications/10-ways-we-can-boost-degree>

Authors' bios

Ali Monzer, University of Birmingham (UK)

Dr Ali Monzer is a Teaching Fellow at the University of Birmingham who is a dedicated educator and researcher in geotechnical engineering, with expertise in soil-fluid interaction and sustainable construction materials. He holds a PhD in Geotechnical Engineering from the University of Birmingham, where he developed advanced computational models to assess ground stability in relation to leaking pipelines. As a Teaching Fellow, Dr Monzer plays a key role in curriculum development, laboratory coordination, and student mentoring across civil engineering modules. His commitment to innovative pedagogy enhances student learning through hands-on experimentation and real-world applications. Beyond academia, Dr Monzer has made significant research contributions to geotechnical asset management, publishing his work in leading geotechnical journals and conferences. Through his industry collaborations, Dr Monzer strengthens the connection between academic research and real-world engineering challenges. His dedication to education and geotechnical innovation drives knowledge exchange and inspires the next generation of engineers.

Dexter Hunt, University of Birmingham (UK)

Dr Dexter Hunt is an Associate Professor at the University of Birmingham who has been active in the field of “Sustainability” and “Underground Space” (in their broadest sense) since 2003. He currently is a mentor for DAs’ on the MSc/DA and therein leads and supports modules in Analytics, Geotechnical Asset Management, Numerical Analysis and Soil Mechanics. In addition, he is currently helping support the development of a DA standard for Tunnel Engineering in collaboration with an industrial trailblazer group. Dr Hunt has authored > 150 publications (>70 in refereed international journals – winning both the Trevithick and Asset Management Awards for best paper in a journal). The Net Zero Together Bootcamp he helped develop and deliver in 2023-24 received a “highly commended” award from The Institute of Civil Engineers for its contribution towards education.

Ian Jefferson, University of Birmingham (UK)

Professor Ian Jefferson is a Professor of Geotechnical Engineering at the University of Birmingham, with over 30 years of experience delivering education at a master level to Geotechnical Engineers, having led MSc Geotechnical Engineering programmes at both Nottingham Trent University and University of Birmingham in the UK. In partnership with Dr Royal facilitated and supported the industry trail blazer which developed the DA standard for Geotechnical Engineering and more recently with Dr Hunt in the development of the Tunnel Engineering L& DA standard. He has an extension research portfolio with a focus on Geohazards, Ground Improvements and Geo-structures, and more recently includes sustainable geotechnics, and is currently a UK representative of the ISSMGE Technical Committee TC 307 Sustainable Geotechnics. More recently, he led a 6-year project that supported over 350 small and medium enterprises in the UK to deliver new construction products from alternative waste materials of low carbon impact.

Alexander Royal, University of Birmingham (UK)

Dr Alexander Royal is an Associate Professor at the University of Birmingham who is active in research focusing on engineered barriers for groundwater/contamination plume migration, soil-water interactions and reuse of waste materials as viable resources in geotechnical engineering applications. Whilst at the University of Birmingham, he has taught the Master's level geotechnical engineering programmes for 20 years, acted as the programme Convener for 12 years and overseen two fundamental redesigns of the programmes in that period. Having contributed to the development of the Degree Apprenticeship Standard in Geotechnical Engineering he implemented the new Degree Apprenticeship in Geotechnical Engineering programme and acts as its convener. The Super-Cube competition he helped develop received a "highly commended" award from a regional branch of the Institution of Civil Engineers for its contribution towards education.

Two decades of evolution of study program on Geotechnical Engineering at the Faculty of Civil Engineering in Skopje

J. Br. Papić, J. Josifovski, I. Peševski, M. Jovanovski & M. Maraš

Ss. Cyril and Methodius University, Skopje, North Macedonia

papic@gf.ukim.edu.mk, jjosifovski@gf.ukim.edu.mk, pesevski@gf.ukim.edu.mk,
jovanovski@gf.ukim.edu.mk, maras.marko@outlook.com

ABSTRACT: North Macedonia has a long tradition of organizing postgraduate studies in geotechnical engineering, aimed at deepening the theoretical and scientific knowledge of graduate engineers. However, our country still faces a lack of educated and specialized professionals in the field of geotechnical engineering. In order to fill part of the gap, in the academic year 2005/06, studies in geotechnics began to be developed according to the 3+2+3 model. Starting from 2012, re-accreditation was carried out every five years. The last re-accreditation faced many challenges, including a decline in the number of students enrolling not only in this particular program but also in civil engineering and technical and natural faculties in general. The paper will briefly discuss the evolution of study program in geotechnics, with a particular focus on the current version.

Keywords: geotechnical engineering, study program, re-accreditation,

1 Introduction

The origins of geotechnical engineering in Macedonia date back to 1949 with the establishment of the Technical Faculty at the Ss. Cyril and Methodius University (UKiM) in Skopje. The faculty initially consisted of two departments: Civil Engineering and Architecture. At that time, the Chair of Geotechnics (then known as the Chair of Soil Mechanics, Foundation Engineering, and Geology) was founded by Prof. Kiril Žernovski. Prof. Žernovski, who had previously served as Mayor of Skopje and was Deputy Minister for Civil Engineering since 1947, was a member of the selected commission that established the Technical Faculty. He was also among the first three elected professors at the faculty, teaching the Foundation Engineering course. Being familiar with geotechnical engineering and its importance in construction in the post-war period, he established the Laboratory for Geotechnics between 1950 and 1952, followed by the Field Laboratory in 1959.

After several administrative reorganizations, the Faculty of Civil Engineering in Skopje (FCE SK) was established in 1975, offering a Civil engineering (CE) study program within several departments. Over the decades, departments focusing on Structural engineering, Roads and railways, and Hydraulic structures engineering attracted the most students and remained active. In 1977, a study program in Geodesy (Gd) was also introduced. Meanwhile, postgraduate programs in these fields, as well as in Geotechnical engineering (GtE), were developed.

Despite a long tradition of organizing postgraduate studies, aimed to deepen the theoretical and scientific knowledge of graduate engineers, a lack of educated and specialized professionals in the field of geotechnical engineering has been observed in the country. In order to fill part of the gap, in 2003 the FCE SK participated in an EU-funded Tempus project SCM-C006B03-2003 entitled "Study Program for Geotechnics". Based on this project, studies in Geotechnics were developed according to the 3+2+3 model (i.e., 1st cycle: 3 years Bachelor's program, 2nd cycle: 2 years Master's program and 3rd cycle: 3 years PhD program) starting in the 2005/06 academic year, following the criteria proposed by the European credit-transfer system (ECTS) (Vitanov et al., 2005).

2 Challenges

Many countries worldwide are characterized by low levels of investment in research and innovation. This is due to various factors, including:

- Reliance on economic sectors that do not prioritize or require substantial research investment;
- Political and economic instability;
- Underdevelopment of primary and secondary education systems;
- Lack of collaboration between the public and private sectors.

These challenges contribute to the 'brain drain': many of the most qualified young individuals emigrate in search of better job opportunities, leaving their home country unable to recover the investment made in their education or benefit from the achievements of their careers, thus perpetuating their country's stagnant situation. Moreover, the Mediterranean region has historically maintained strong patriarchal structures, and traditional roles have contributed to the gender gap in various areas, including civil engineering. Furthermore, disinformation and erosion of public trust in scientific expertise can exacerbate these issues by hindering the implementation of evidence-based solutions and fostering resistance to necessary but complex policy measures. To address these pressing issues, more resources must be invested in research and in finding solutions that will require joint efforts of national and international actors through collaborative networking and sharing of experiences. The first step is to raise collective awareness and emphasize the need for cooperation to overcome these challenges.

Similar trends can be observed at the local, Balkan, level. Due to the continued migration of young people and the decline of large families, the number of students in primary and secondary schools has been steadily decreasing over the past 15 years. Some of these trends began even a few years earlier, coinciding with the establishment of a study program in geotechnics. Specifically, from 2010 to the present, in North Macedonia there has been a decrease of:

- ~30,000 students in the total number of students in primary schools (~15%);
- ~15,000 students in the total number of students in secondary schools (~30%);
- ~6,000 secondary school graduates (~30%).

These factors, combined by the growing influence of technology, have led to a significant decrease in interest in studying technical and natural sciences. In the last decade, it has been consistently observed that the total number of students enrolled in standard technical faculties at UKiM (Architecture, Civil Engineering, Electrical Engineering, Mechanical Engineering, and Technology and Metallurgy) is less than half the number of students enrolled in the Faculty of Information Sciences. Additionally, it is not uncommon to encounter students who have graduated or even obtained a master's degree from the FCE SK, only to pursue further studies in computer science through short-term courses. Some numbers and trends are summarized in Figure 1.

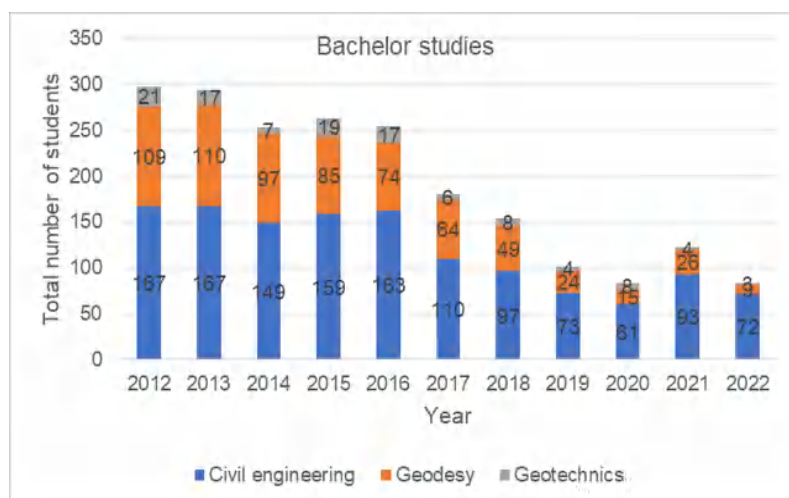


Figure 1. Number of students enrolling in civil engineering, geodesy, and geotechnics at the FCE SK in the period 2012-2022

To boost interest in studying civil engineering, geodesy, and geotechnics, the FCE SK has developed and implemented a strategy over the years, not limited to promotion via media and at schools, weekend camps etc. Similar measures are being taken in many other countries across Europe and the world. One local key source of support is the Macedonian Association for Geotechnics (MAG), which covers the tuition fees for students enrolling in the first and second cycles of studies in GtE.

3 Development of the study program

Geotechnical issues in construction, mining, and environmental protection have always been present in our country, arising in nearly every construction project. As a result, core geotechnical disciplines such as Engineering Geology, Soil Mechanics, and Foundation Engineering are taught as compulsory subjects within the CE study program at the FCE SK, while Rock Mechanics has also been taught for a long period at the Roads and railways and at Hydraulic structures departments. Additionally, certain electives are offered within the Gd study program.

Moreover, the Faculty continually expands, improves, and enriches its activities, adapting to global trends and standards, as well as to the needs of the economy and society (Papić et al., 2011). The curricula and programs for all three of its study programs – CE, Gd, and GtE – are regularly updated to reflect advancements in science and technology, changes in other societies, and the demands of the construction industry and related economic branches. Thanks to this approach, graduates from the faculty have proven to be skilled professionals who are well-regarded not only in our country and the region but also globally (Rakić et al., 2013).

These adaptations in the curricula were also influenced by changes in the Law on Higher Education (LHE) and corresponding university rule books, which required re-accreditation every five years. Thus, re-accreditation occurred in 2012, during which a comprehensive selection of subject programs was introduced to meet the LHE requirements. This model was somewhat followed during the next re-accreditation in 2017. The most recent re-accreditation was carried out in 2022.

Generally, the main goal of the GtE study program is to provide advanced multidisciplinary skills in geotechnics, field investigations (as future work environment), foundation engineering, and various types of geotechnical designs, while staying current with technological advancements and addressing environmental challenges. Additionally, during the preparation of the study program for re-accreditation in 2022, the following aspects were considered:

- Maximum compatibility of the core subjects with the existing programs offered at the FCE SK;
- Maintaining the balance between the core, theoretical, and professional subject programs;
- Ensuring a proper number of electives from various categories;
- Experiences from similar study programs at universities across Europe and the world;
- Our own experiences, based on the unique characteristics of this field in our region;
- The legal framework outlined by the Law on Higher Education;
- Respecting the material and personnel resources available for this field at the FCE SK;
- The criteria present at the Chamber of Certified Architects and Certified Engineers;
- Incorporation of literature and subjects from previous accreditations.

4 Established Program

In previous re-accreditations, by the then-current version of the LHE, the percentage of optional professional subjects varied in both study cycles, reaching over 40%, from different categories and origins: general university, professional civil engineering, vocational geotechnical engineering etc. (Josifovski et al., 2013). For this purpose, subjects related to geology, geotechnics, ecology, and other fields were selected and included. However, with the most recent change, which was also reflected in the University's Regulations three years ago, the scope of optional subjects has significantly decreased.

There was also a dilemma about whether to discontinue the study program in the 1st cycle and to retain only a few elective geotechnical courses in the final semester, given the decline in interest in studying natural sciences (e.g., geology and geophysics) and technical sciences (particularly civil engineering).

However, this was contrasted by an increasing demand for geotechnical engineers, driven by significant capital investments in complex geological conditions. Since the courses in question were still "active", with a solid foundation of existing literature, a decision was made to combine related subjects or redistribute certain topics into similar courses. While a few subjects were discontinued, others were moved to the 2nd cycle. The lists in Table 1 and Table 3 include courses planned for the 1st and 2nd cycles of studies from 2023–2028, securing variety and expressing attractiveness. According to the LHE, the program will allow students to take any necessary remaining or additional exams until 2031.

Table 1. Distribution of subjects through semesters at the first cycle of studies ("Elaborate...", 2022a)

Semester	No.	Geotechnical Engineering Study Program	Credits	Study program	Lectures	Practices
I	1	Mathematics 1	8	CE	4	4
	2	Statics	8	CE	3	3
	3	Applied geometry	3	CE	1	2
	4	Engineering geology	5	CE	2	2
	5	Engineering structures	6	CE	3	3
Total:			30		13	14
II	6	Applied hydrogeology	6	GtE	3	3
	7	Kinematics and dynamics	5	CE	3	2
	8	Geodesy	5	CE	2	2
	9	Engineering materials	5	CE	3	2
	10	CAD oriented software	4	CE	2	2
	11	Regulation in civil engineering / Water protection	5	CE	2	2
Total:			30		15	13
III	12	Strength of materials	7	CE	3	3
	13	Technology of concrete	5	CE	3	2
	14	Roads and railways	6	GtE	3	3
	15	Fluid mechanics	7	CE	3	3
	16	Basics of geoinformation systems	5	Gd	3	2
Total:			30		15	13
IV	17	Soil mechanics	7	CE	3	4
	18	Rock mechanics	6	GtE	3	2
	19	Environmental geotechnics	7	GtE	3	3
	20	Water supply and sewerage	5	CE	3	2
	21	Organization and machines at sites	5	CE	3	2
Total:			30		15	13
V	22	Reinforced concrete	5	CE	3	3
	23	Geotechnical investigations	7	GtE	3	3
	24	Tunnels	5	CE	2	2
	25	Hydraulic structures	5	CE	3	2
	26	Foundation engineering 1	8	GtE	3	3
Total:			30		14	13
VI	27	Bridges / Management in civil engineering	5	CE	2	2
	28	Earth structures and geosynthetics	5	GtE	3	2
	29	Foundation engineering 2	5	GtE	3	2
	30	Soil improvement / Construction pit protection	5	GtE	3	2
	31	Rock improvement / Basics of engineering seismology	5	GtE	3	2
	32	Bachelor's thesis	5	GtE	0	5
Total:			30		14	15

Throughout the semesters, some of the subjects are shared with students from the CE and Gd study programs. The numerical representation is given in Table 2, where it can be noted that the ratio of subjects from CE and Gd to those from GtE is 2:1. Beside respecting the aspects given above in Section 3, this scheme enables closer communication, cooperation and networking among students within particular class generation (which was also noted to be decreasing), from which they would benefit both through studies (delivering homework, preparing exams, participating in university sport leagues) and further in professional carrier (also approved through individual interviews with students and engineers).

Table 2. Classification of subjects at the first cycle of studies by origin/study program

Study program	Semester						Sum
	I	II	III	IV	V	VI	
CE	5	5	3	3	3	1	20
Gd			1				1
GtE		1	1	2	2	4	10

The schedule of courses for the 2nd cycle of studies in GtE is presented in Table 3. Although advancing the topics, still one of the elective geotechnical subjects from the 1st cycle of studies remain available for taking. As illustrated below, only three courses are not particularly prepared for the students of GtE, i.e., organized by the Chair of Geotechnics.

Table 3. Distribution of subjects through semesters at the second cycle of studies ("Elaborate...", 2022b)

Semester	No.	Geotechnical Engineering Study Program	Credits	Study program	Lectures	Practices
I	1	Mathematics 2	8	Gd	4	4
	2	Theoretical soil mechanics	6	GtE	3	2
	3	Geotechnical monitoring	4	GtE	2	2
	4	Landslides and slope stabilization	6	GtE	3	3
	5	Numerical methods in geotechnics	6	GtE	3	3
Total: 30					15	14
II	6	Selected problems in the foundation	7	GtE	3	2
	7	Soil improvement / Construction pit protection / Physical modelling in geotechnics	5	GtE	3	2
	8	Elasticity and plasticity	5	CE	3	2
	9	Geotechnics at mining works	6	GtE	3	2
	10	Geotechnical modelling	7	GtE	3	3
Total: 30					15	11
III	11	Dynamics of soils and foundations	6	GtE	3	2
	12	Estimation of engineering and environmental risks in geotechnics	6	GtE	3	2
	13	Rheology of soils and rocks	6	GtE	2	2
	14	Geotechnics of underground works and structures / Earth pressure and retaining structures	7	GtE	3	3
	15	Hydrology / Embankment dams / Repair and strengthening of concrete structures / BIM / Probability and statistics / Remote sensing in geotechnics	5	CE / Gd	3	2
Total: 30					14	11
IV	16	Practice	6	GtE	0	4
	17	Master thesis	24	GtE	0	20
Total: 30					0	24

As a result of these adaptations, along with an intensified campaign in secondary schools across Skopje and the rest of the country, the most recent accreditation period saw an increase in the number of students enrolled in the GtE study program (Table 4). Furthermore, the effort to dispel the myth that CE and GtE are 'male' professions was successful, as reflected in a balanced gender ratio.

Table 4. Number of enrolled students per study program at the FCE SK after re-accreditation in 2022

	Civil Engineering	Geodesy	Geotechnical Engineering	Total
2023	66	8	7	81
2024	80	18	9	107

5 Some European Experiences

Regarding the organization of study programs based on the 3+2 system, it is important to note that the majority of European civil engineering faculties are also structured according to the ECTS 3+2 system. Examples include the university centres in Lausanne and Zurich, which, along with Imperial College London, are among the highest-ranked European universities on the Shanghai Ranking. This teaching model is also implemented at many civil engineering faculties in Germany, as well as universities from the former Yugoslavia with which Skopje maintains close communication and cooperation (such as Belgrade, Zagreb, and Ljubljana), at the Vienna University of Technology and others.

When comparing study programs, there is notable overlap with the subject offerings at the École Polytechnique Fédérale de Lausanne (<http://sgc.epfl.ch>), which offers a substantial amount of geotechnical content. This includes courses such as: Geology I, Geology II, Soil Mechanics, Rock Mechanics, Groundwater Movement, Geotechnics and Foundations, Geomechanics, Geotechnical Engineering, Geotechnical Investigations, Underground Works, Foundation Engineering I, etc. The University of Durham, United Kingdom (<http://www.dur.ac.uk>), which offers a one-year specialized program in Geo-Engineering, divided into three areas: Engineering Geology, Geotechnical Engineering, and Geoenvironmental Engineering, can also be mentioned. Additionally, the Technical University of Graz (<http://www.tugraz.at>) has a Faculty of Civil Engineering with a Geotechnics Department offering courses such as: Engineering Geology, Rock Mechanics and Tunnelling, Soil Mechanics and Groundworks, Investigations in Rock Mechanics, Soil Investigations, Geosynthetics in Earthworks, Numerical Methods in Geotechnics, and Soil and Rock Improvement and Grouting. The program is also comparable to the Geotechnical Faculty in Varaždin, which is an integral part of the University of Zagreb.

This comparability is encouraging and is highlighted when promoting the study programs to high school students.

6 What Next?

Geotechnics, as both a scientific and professional field, has been present in Macedonia for many years, and continues to be a significant area of expertise among professionals in construction and geology. Historically, Macedonian experts were generally organized within the respective Yugoslav associations for soil mechanics and foundation engineering, engineering geology and hydrogeology, rock mechanics, and underground works, among others. Geotechnical engineers in our country are organized through the MAG, which has been active since 1998. In 2001, it became a full member of the ISSMGE, and in 2017, it was recognized as a national group within ISRM. Among the numerous international events, visits, and lectures organized by the MAG, the European Young Geotechnical Engineers Conference in 2024 stands out as particularly significant for students.

At the same time, it is important to highlight that, in accordance with the Law on Construction, geotechnics is granted special authorizations for execution, design, supervision, and revision of constructions through the Chamber of Certified Architects and Certified Engineers (CCACE). This makes geotechnics part of the preliminary list of regulated professions in our country. To further strengthen the role of engineers, members of the geotechnical department at the CCACE have developed Lists of Fees for engineering services in both building construction and civil engineering. These are expected to be approved soon by the relevant Ministry, with the goal of encouraging young people to pursue careers in geotechnics and continue working in this field.

7 Concluding remarks

During the implementation of the last re-accreditation, which began in 2023, the Chair of Geotechnics, along with other chairs, has faced significant challenges, primarily due to the drastic decrease in the number of high school students and their declining interest in studying natural sciences (e.g., geology and geophysics) and larger number of technical sciences. Amid discussions about whether to continue or cancel the geotechnics study program, a difficult but courageous decision was made to maintain it as a separate program, unlike the Structural engineering, Roads and railways, and Hydraulic Structures, which are no longer separately offered within the Civil Engineering study program in the 1st study cycle, but there they are at the 2nd cycle.

To offer students more variety and flexibility in their professional development and maintain the attractiveness of the study program for GtE among young people, a compromise approach was adopted for the 1st cycle. This approach aligns the 1st cycle closely with the CE study program, allowing students from both programs to take a greater number of common courses. As students advance, they are gradually introduced to geotechnical subjects in the later semesters. Thus, the ratio of civil engineering to geotechnical engineering subjects is 2:1.

On the other hand, the 2nd cycle is focused mainly on specialized subjects, with only three out of 17 courses not covered by the Chair of Geotechnics.

The courses offered include those that can be categorized as distinctly geotechnical, along with others focused on geology (which slightly help address the shortage of geology staff while also catering to students with interests in hiking or scouting), ecology (to address contemporary challenges), numerical modelling (to cater to students with interest in software engineering), law and financial affairs (to serve answers on topics frequently met in the media) and advanced technology (to monitor global achievements and trends), among others. Thanks to the intensified campaign to promote the study programs, along with the freshness and novelty of the programs accredited in 2022, the number of students enrolling in the 1st cycle of studies at Geotechnical engineering, as well as in Civil engineering and Geodesy, is increasing. We remain hopeful that this positive trend will continue without any signs of reversal, for which joint efforts by faculty and professional associations are further necessary in order to serve the multiple aspects and to resist the negative challenges that have been noticed worldwide.

References

- Elaborate on re-accrediting the study program on geotechnical engineering – I cycle of studies. (2022a). Ss. Cyril and Methodius University, Faculty of Civil Engineering, Skopje, R. N. Macedonia. (In Macedonian)
- Elaborate on re-accrediting the study program on geotechnical engineering – II cycle of studies. (2022b). Ss. Cyril and Methodius University, Faculty of Civil Engineering, Skopje, R. N. Macedonia. (In Macedonian)
- Josifovski, J., Jovanovski, M., Papić, Br. J., Gjorgjevski, Sp., Peševski, I. (2013). Some novelties in the study program for geotechnics. 5th conference Geotechnical aspects of civil engineering, pp. 425-430, Society of engineers and technicians, Belgrade, Serbia. (In Serbian)
- Papić, Br. J., Vitanov, V., Jovanovski, M., Peševski, I., Krsteska-Papić, B. (2011). Modeling exercises as a valuable tool for shaping students' knowledge, pp. 277-282. Faculty of Civil Engineering and Architecture, Niš, Serbia.
- Rakić, Dr., Šišić, R., Papić, J. Br., Zafirovski, Zl. (2013). Designing a researcher, 13th International Multidisciplinary Scientific Geoconference, pp. 399-406, Albena, Bulgaria.
- Vitanov, V., Jovanovski, M., Papić, Br. J., Josifovski, J. (2005). Study program for geotechnics. 1st conference Geotechnical aspects of civil engineering, Society of engineers and technicians, Belgrade, Serbia. (In Serbian)

Authors' bios

Jovan Br. Papić, Ss. Cyril and Methodius University in Skopje (N. Macedonia)

He is a professor at the Chair of Geotechnics at the Faculty of Civil Engineering in Skopje (FCE SK). After graduating in Civil engineering at the Structural department at FCE SK, Jovan obtained a M.Sc. in geotechnical engineering at the University of Belgrade and a Ph.D. at the University of Niš, both in Serbia. His teaching and work are related to soil mechanics, slope stability, retaining walls, Eurocode 7, environmental geotechnics, etc. He has been involved in developing the study program for geotechnics at affiliated faculty from the very beginning of its initiation. Under his mentorship, several groups of students were highly awarded at international competitions for student projects.

Josif Josifovski, Ss. Cyril and Methodius University in Skopje (N. Macedonia)

Josif Josifovski is a Full Professor at the Ss. Cyril and Methodius University, FCE SK, where he teaches a group of subjects in the study programs for Civil and Geotechnical Engineering: Geotechnical Engineering, Foundation Design, Ground Investigation, and Ground Improvement to Undergraduate, and Numerical Modelling in Geotechnics, Special Geotechnical works, and problems in Foundation Engineering to Postgraduate. He also teaches courses in Unsaturated Soil Mechanics, Geothermally active structures, and Soil-Structure Interaction to Ph.D. students. He holds a Master's degree in Computational Engineering from the Ruhr University in Bochum (Germany) and a Ph.D. degree from International doctoral studies in engineering SEEFORM (South-East Europe Formation for Master and Ph.D. studies) with a study stay at the University of Technology in Hamburg. In both cases, he was supported with a scholarship from the German Academic Exchange Service or DAAD.

Igor Peševski, Ss. Cyril and Methodius University in Skopje (N. Macedonia)

Prof. Igor Peshevski is a member of the Chair of Geotechnics at the FCE SK. He graduated in geology from the Faculty of Mining and Geology (FMG) at the Goce Delčev University in Štip in 2008 and obtained his master degree in 2009 and his doctorate in 2015 in geotechnics at the FCE SK. He teaches Engineering geology, Applied hydrogeology, Rock Mechanics, Rock Improvement, Geotechnical investigations, Landslides and slope stabilization, Assessment of engineering and environmental risks in geotechnics, and Geotechnics at mining works. His scientific work focuses on landslide characterization, engineering-geological assessments, and rock mass characterization. In 2024 he chaired the organization of the European Young Geotechnical Engineers Conference held in North Macedonia.

Milorad Jovanovski, Ss. Cyril and Methodius University in Skopje (N. Macedonia)

He is professor at Chair of Geotechnics at the FCE SK. He graduated geology from the FMG in Štip in 1988, obtained his master degree in 1993 at the Faculty of Geology and Mining in Belgrade and his doctorate in 2001 in geotechnics at the FCE SK. He teaches the subjects: Engineering geology, Applied hydrogeology, Rock Mechanics, Rock Improvement, Landslides and assessment of risks in geotechnics etc. His scientific work focuses on engineering geology and rock mechanics problems, rock mass classification, large scale rock mechanics tests etc. He was a Chair of the XVI Danube-European Conference for Geotechnical Engineering held in Skopje and acts as a Vice President at large at International Society for Rock Mechanics and Rock Engineering.

Marko Maraš, Ss. Cyril and Methodius University in Skopje (N. Macedonia)

After graduating geotechnical engineering at the FCE SK, Marko is progressing with master studies in geotechnical engineering at the same faculty. During them, he spent 6 months on an internship in Germany. Meanwhile, he conducted research related to the physical modelling of wind turbine foundations. He is actively engaged as a collaborator of the Chair of Geotechnics, both as a teaching assistant and in laboratory, field, and office work and practices.

Introducing geotechnical engineering discipline to K-12 STEM teachers for professional development

H. Seo¹ & M. Yi²

¹*Department of Civil, Environmental and Construction Eng., Texas Tech University, Lubbock, USA*
hoyoung.seo@ttu.edu

²*College of Education, Texas Tech University, Lubbock, USA*
minju.yi@ttu.edu

ABSTRACT: This paper presents a case study on integrating geotechnical engineering into K-12 education through two initiatives: (a) a professional development workshop for K-12 STEM teachers and (b) the incorporation of geotechnical engineering topics into an undergraduate course for preservice math and science teachers. These efforts involved the development of three learning modules aligned with the K-12 curriculum to establish real-world connections and foster student interest in geotechnical engineering through their teachers. The modules focus on: (i) linking the coefficient of friction to the soil friction angle, (ii) relating an object on an inclined surface to slope stability analysis, and (iii) demonstrating the effectiveness of a logarithmic scale for representing data with a wide range of magnitudes using a soil particle size distribution curve. Survey responses from participating teachers highlighted the modules' effectiveness in potentially enhancing their classroom learning.

Keywords: *Geotechnical engineering, STEM, Outreach, K-12 Teachers*

1 Introduction

In the United States, K-12 education encompasses kindergarten through 12th grade, covering primary and secondary education before college or university. In Texas, elementary school typically includes Grades K through 5, middle school consists of Grades 6 through 8, and high school comprises Grades 9 through 12. Mathematics and science courses in K-12 education play a crucial role in preparing students for careers in science, technology, engineering, and mathematics (STEM) fields. However, many students struggle with these subjects, which can reduce their motivation to pursue STEM careers. A significant challenge is the perceived lack of real-world relevance in math and science concepts. When students do not see practical applications or connections to their daily lives, they often lose interest and disengage (Osborne et al., 2003).

To spark students' interest in math and science from an early age, college and university educators have introduced geotechnical engineering into K-12 education through outreach programs (Fiegel et al., 2000; Suescun-Florez et al., 2013; Raymond and Bronner, 2020). Geotechnical engineering is particularly well-suited for this purpose because it incorporates mathematics, solid mechanics, and fluid mechanics (Suescun-Florez et al., 2013), while also dealing with soil and water—two of the most abundant natural materials on Earth. Additionally, geotechnical engineering has been introduced to K-12 teachers as part of professional development initiatives (Ajmera et al., 2024). Providing learning opportunities for teachers is highly effective because when they recognize real-world connections, teachers can better integrate these concepts into their lessons, making them more relatable to students.

Margot & Kettler (2019) performed a systematic literature review on teachers' perception of STEM integration and found that "teachers believe that well-organized and frequently available professional learning opportunities would facilitate successful STEM initiatives." Teachers at various career stages reported that they experienced significant improvements in their confidence, knowledge, and ability to

teach STEM after participating in professional development programs. Furthermore, teachers expressed a need for ready-to-use STEM problems that could be implemented in their classrooms immediately and aligned with grade level curriculum standards they teach.

In this paper, we present three learning modules related to geotechnical engineering, designed for K-12 teachers. These modules are well aligned with the K-12 curriculum and focus on: (i) linking the coefficient of friction to the soil friction angle (Module 1), (ii) relating an object on an inclined surface to slope stability analysis (Module 2), and (iii) demonstrating the effectiveness of a logarithmic scale for representing data with a wide range of magnitudes using a soil particle size distribution curve (Module 3). Each module includes discussions on its relevance to real-life applications.

These learning modules were introduced in a professional development workshop held at Texas Tech University in June 2019 for in-service K-12 STEM teachers from across West Texas. Additionally, they were incorporated into an undergraduate course in the College of Education (EDML 4375: Integrated Mathematics and Science Methods) to support preservice secondary math and science teachers.

2 Development of learning modules

2.1 Guiding Principles

When developing the learning modules, we followed three guiding principles:

Principle 1: Alignment with K-12 Mathematics and Science Standards. The modules were designed to align with *Texas Essential Knowledge and Skills (TEKS)*. TEKS is the state curriculum standard that outlines what students in Texas public schools are expected to learn at each grade level and in each subject. It is developed by the Texas Education Agency (TEA) and serves as the foundation for instruction in K-12 education across various subjects, including mathematics, science, English language arts, social studies, and career and technical education.

Principle 2: Incorporation of Hands-on Activities. Each module includes a hands-on activity to promote kinesthetic and inquiry-based learning. Participants join the instructor in performing these activities, allowing them to experience key principles in an interactive manner. Additionally, the activities require no special equipment, making them easy to implement in K-12 math and science classrooms.

Principle 3. Emphasis on Real-World Connections. Since the primary audience for these modules is teachers without formal training in engineering, each module explicitly highlights real-world applications. This approach helps teachers introduce geotechnical engineering concepts to their students in meaningful ways, potentially enhancing student learning and sparking interest in the field.

2.2 Module 1 – Friction Angle

2.2.1 Background

Friction is introduced in Grade 6 science as a force that opposes relative motion between objects in contact. In high school Advanced Placement (AP) physics, the concept of friction is further expanded to distinguish between static friction and kinetic friction. In geotechnical engineering, the friction angle (ϕ) is a key parameter used as a measure of the shear strength of a granular soil. It depends on the frictional resistance between soil particles and is closely related to the coefficient of friction between two objects. In Module 1, participants review the concept of friction and force balance through a hands-on activity. They also measure the coefficient of static friction (μ_s) and represent it as an angle, which is extended into the friction angle of a granular soil with an introduction of direct shear tests. The hands-on activity is easy to implement and requires only a digital hanging luggage scale, a rope, dumbbells, and a flat object. Table 1 summarizes Math and Science TEKS that can be taught through this module.

Table 1. TEKS (Texas Essential Knowledge and Skills) that can be taught through Module 1

TEKS for Mathematics	TEKS for Science
[Grade 8, (5) Proportionality] (A) represent linear proportional situations with tables, graphs, and equations in the form of $y = kx$. [Grade 8, (5) Proportionality] (D) use a trend line that approximates the linear relationship between bivariate sets of data to make predictions. [Geometry, (9) Similarity, proof, and trigonometry] (A) determine the lengths of sides and measures of angles in a right triangle by applying the trigonometric ratios sine, cosine, and tangent to solve problems. [Precalculus, (4) Number and Measure] (I) use vectors to model situations involving magnitude and direction. [Statistics, (7) Bivariate data] (A) analyze scatterplots for patterns, linearity, outliers, and influential points. [Statistics, (7) Bivariate data] (B) transform a linear parent function to determine a line of best fit.	[Grade 6, (7) Force, motion, and energy] (A) identify and explain how forces act on objects, including gravity, friction, magnetism, applied forces, and normal forces, using real-world applications. [Grade 6, (7) Force, motion, and energy] (B) calculate the net force on an object in a horizontal or vertical direction using diagrams and determine if the forces are balanced or unbalanced. [Grade 6, (7) Force, motion, and energy] (C) identify simultaneous force pairs that are equal in magnitude and opposite in direction that result from the interactions between objects using Newton's Third Law of Motion. - Physics, (1) Scientific and engineering practices] (F) organize quantitative and qualitative data using bar charts, line graphs, scatter plots, data tables, labeled diagrams, and conceptual mathematical relationships.

2.2.2 Instruction

The instructional approach for Module 1 is presented below:

- Review the concept of friction by explaining it as the force resisting the relative motion between two objects in contact.
- Differentiate between static friction (which prevents objects from moving relative to each other because the applied force and resisting friction are balanced) and kinetic friction (which occurs when objects move against each other).
- Explain the maximum frictional resistance (f_{max}) at the interface between two objects occurs just before motion begins and is defined as the product of the coefficient of static friction (μ_s) and the normal force (F_N) exerted on the interface as follows:

$$f_{max} = \mu_s F_N \quad (1)$$
- Remind participants that μ_s can be determined if F_N and f_{max} are known, and inform them they will measure these values through a hands-on activity.
- Ask a participant volunteer to measure the weights of a dumbbell and a flat object three times each using a digital hanging scale and compute the average weights of both objects. (To save time, these weights can be determined before class begins.)
- Position the flat object on a table and place the dumbbell on top. Explain that the combined weight of the dumbbell and flat object represents the normal force $F_{N,avg}$ acting between the flat object and the table.
- Attach the digital luggage scale to the flat object using a rope and slowly pull the digital scale until the flat object just starts moving (see Fig. 1). Read the value displayed on the digital luggage scale. Explain to participants that the digital luggage scale is set to a mode that records and displays the maximum force during pulling, and the displayed value represents the maximum frictional resistance (f_{max}).

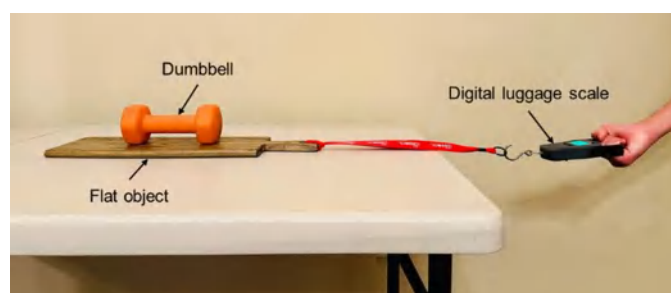


Figure 1. A photo showing hands-on activity in Module 1

- (h) Perform three trials and compute the average maximum frictional resistance $f_{max,avg}$.
- (i) Record $F_{N,avg}$ and $f_{max,avg}$ as Test 1.
- (j) Add more dumbbells to increase the normal force and repeat Steps (g) through (i) two more times (for Tests 2 and 3). This process provides $f_{max,avg}$ under three different weights in total.
- (k) Enter the $F_{N,avg}$ and $f_{max,avg}$ from Tests 1, 2, and 3 into a spreadsheet.
- (l) Create a scatter plot and add a linear trend line with the intercept set to zero. Display the equation of the line and the coefficient of determination (R^2) on the plot.
- (m) Ask participants to determine the coefficient of static friction μ_s from the plot and calculate an angle (ϕ) of the trend line with respect to the horizontal axis (i.e., $\phi = \tan^{-1}(\mu_s)$). Fig. 2 shows the data and plot obtained from the undergraduate course for K-12 preservice math and science teachers.

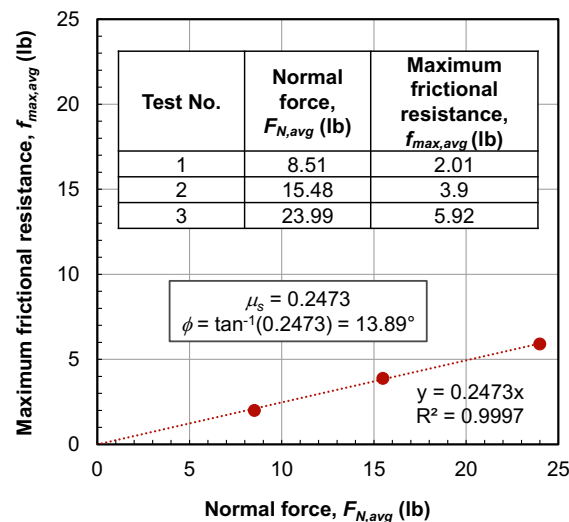


Figure 2. Determination of friction angle using data obtained from the hands-on activity in Module 1

- (n) Then, introduce the direct shear test to participants (the direct shear test is not actually performed, but the direct shear test box is passed around to participants). Explain that the granular soil such as sand is placed in the shear box, creating a soil-to-soil contact interface. Further explain that a normal force is applied by placing a vertical load on top of the soil specimen and the upper half of the shear box is pushed laterally using a controlled motor and that the direct shear test equipment can measure the maximum frictional resistance of the soil. Relate the direct shear tests to the hands-on activity by explaining that the frictional coefficient of the soil-to-soil contact can be determined from direct shear tests, allowing for the calculation of the friction angle. Explain that the friction angle is a critical parameter for assessing the shear strength of a granular soil in infrastructure design, such as bridge foundations. Then, present a slide that shows a shaft resistance (skin friction) of deep foundations for bridge support, and highlight the similarity between the shaft resistance and the frictional resistance explored in Module 1.

2.2.3 Reflections

Participants are typically familiar with the concept of the friction coefficient. However, it is uncommon for them to determine its value experimentally, as they did in Module 1. Many are surprised to observe a strong linear relationship in their measured data. Additionally, some participants are intrigued to learn that engineers rigorously measure the strength of soil—often perceived simply as “dirt”—through experiments like direct shear tests. Seeing the direct connection between friction and infrastructure design generates excitement and enhances their understanding of real-world applications. Module 1 can also be extended into a project-based learning by challenging students (i) to determine the friction coefficients of various material interfaces and (ii) to evaluate and discuss the reliability of the friction coefficient measurements, comparing values obtained from a single measurement versus from an average of multiple trials. This extension encourages critical thinking and reinforces the importance of experimental accuracy in engineering applications.

2.3 Module 2 – Slope Stability Analysis

2.3.1 Background

Module 2 connects slope stability analysis for planar failure to the concept of an object on an inclined plane, a topic covered in high school AP physics. Module 2 introduces the factor of safety and establishes a clear link between friction on an inclined plane and real-world applications. This module also incorporates trigonometry and vector decomposition, reinforcing key mathematical principles. The hands-on activity simulates an object on an inclined plane using a 76-mm (or larger) ring binder, small plastic cups, and water. Participants actively engage by analysing physical relationships, making predictions, and interpreting experimental results. Module 2 aligns well with various TEKS criteria, as summarized in Table 2.

Table 2. TEKS (Texas Essential Knowledge and Skills) that can be taught through Module 2

TEKS for Mathematics	TEKS for Science
[Grade 6, (4) Proportionality] (B) apply qualitative and quantitative reasoning to solve prediction and comparison of real-world problems involving ratios and rates. [Grade 6, (7) Expressions, equations, and relationship] (D) generate equivalent expressions using the properties of operations: inverse, identity, commutative, associative, and distributive properties. [Geometry, (9) Similarity, proof, and trigonometry] (A) determine the lengths of sides and measures of angles in a right triangle by applying the trigonometric ratios sine, cosine, and tangent to solve problems. [Precalculus, (4) Number and Measure] (J) represent the addition of vectors and the multiplication of a vector by a scalar geometrically and symbolically.	[Physics, (1) Scientific and engineering practices] (B) apply scientific practices to plan and conduct descriptive, comparative, and experimental investigations, and use engineering practices to design solutions to problems. [Physics, (5) Science concepts] (B) define scalar and vector quantities related to one- and two-dimensional motion and combine vectors using both graphical vector addition and the Pythagorean theorem. [Physics, (5) Science concepts] (F) calculate the effect of forces on objects, including tension, friction, normal, gravity, centripetal, and applied forces, using free body diagrams and the relationship between force and acceleration as represented by Newton's second law of motion. [Physics, (5) Science concepts] (G) illustrate and analyze the simultaneous forces between two objects as represented in Newton's third law of motion using free body diagrams and in an experimental design scenario.

2.3.2 Instruction

The instructional approach for Module 2 is presented below:

- (a) Present a slide illustrating an object on an inclined surface with force components. Engage participants by asking them to resolve the downward gravitational force (mg) into two components using trigonometry, one parallel to the inclined surface ($mg\sin\theta$) and the other one normal to the inclined surface ($mg\cos\theta$), where m is a mass of the object and θ is an angle of the inclined surface (see Fig. 3(a)).

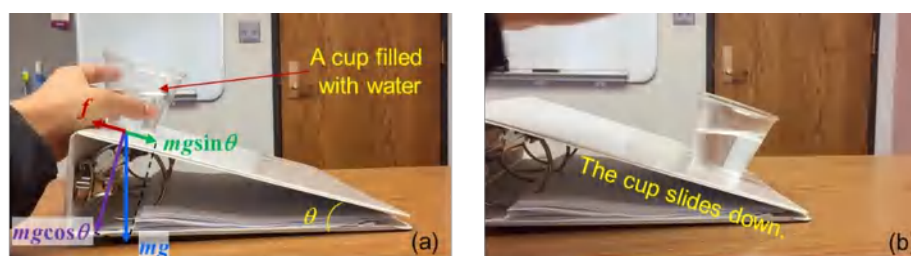


Figure 3. A photo showing hands-on activity with a cup filled with water in Module 2

- (b) Point out that the red vector shown in Fig. 3(a) represents frictional resistance. Then, remind participants that the maximum frictional resistance (f_{max}) is the product of the coefficient of static friction and the normal force ($f_{max} = \mu_s F_N$), as covered in Module 1.
- (c) Introduce the factor of safety (FS) for an object on an inclined surface:

$$FS = \frac{f_{max}}{mg \sin \theta} \quad (2)$$

- (d) Explain the expected behaviour of the object based on FS: (i) if $FS < 1$, the driving force $mg \sin \theta$ exceeds the maximum frictional resistance f_{max} , and the object slide downs, and (ii) if $FS > 1$, the object remains stationary.
- (e) Ask a participant volunteer to put the cup filled with water on top of the binder and release it. The cup slides down (see Fig. 3(b)).
- (f) Ask the volunteer to pour out the water and hold the empty cup on top of the binder.
- (g) Engage participants by asking, "Will the empty cup slide down now?" [Some may predict no because the weight of the cup (or driving force) is now smaller.]
- (h) Ask the volunteer to release the empty cup; it still slides down. (see Figs. 4(a) and 4(b)).

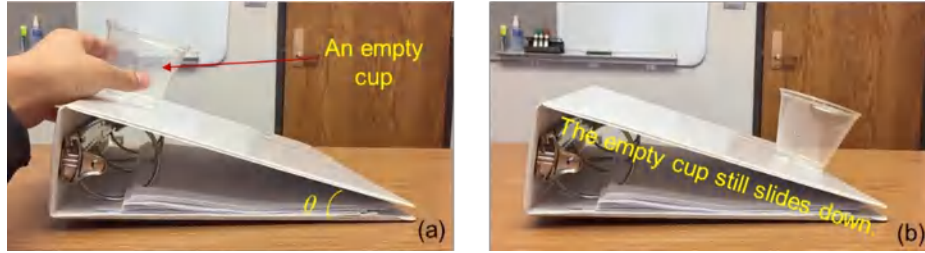


Figure 4. A photo showing hands-on activity with an empty cup in Module 2

- (i) Revisit Eq. (2) and remind participants that f_{max} is the product of the coefficient of static friction and the normal force, $f_{max} = \mu_s F_N$ where the normal force F_N is $mg \cos \theta$. Rearrange and simplify Eq. (2) by substituting f_{max} with $\mu_s mg \cos \theta$ as follows:

$$FS = \frac{f_{max}}{mg \sin \theta} = \frac{\mu_s F_N}{mg \sin \theta} = \frac{\mu_s mg \cos \theta}{mg \sin \theta} = \frac{\mu_s}{\tan \theta} = \frac{\tan \phi}{\tan \theta} \quad (3)$$
- (j) Emphasize that the FS only depends on the angle of the inclined surface θ and the friction coefficient $\mu_s (= \tan \phi)$, and, therefore, the cup will keep sliding down as long as the angle of the inclined surface θ remains greater than the friction angle of the interface ϕ , regardless of its weight mg . Reinforce this concept by explaining further that when the cup is empty, its weight (mg) decreases, which reduces the driving force ($mg \sin \theta$). However, at the same time, the normal force ($mg \cos \theta$) also decreases, leading to a lower maximum frictional resistance. Accordingly, the ratio of driving force to resisting force (i.e., FS) remains the same, meaning that if the cup slid down when full, it would still slide when empty as long as $\theta > \phi$.
- (k) Present a slide with photos of roadway cut slopes. Explain that geotechnical engineers design roadway cut slopes with an FS between 1.2 and 1.5 by adjusting the slope angle after determining soil strength.

2.3.3 Reflections

Most teachers correctly predict that the empty cup will still slide down, but some initially believe it will remain in place because it is lighter. When participants see that the weight term (mg) cancels out and that the factor of safety (FS) depends only on θ and μ_s (or ϕ), they gain a deeper symbolic understanding and accept the outcome. The hands-on activity in Module 2 connects back to Module 1 by demonstrating that the coefficient of static friction (μ_s) can also be determined by identifying the critical angle at which an object begins to slide down on an inclined surface (i.e., $FS = 1$). This reinforces the friction concepts introduced in Module 1. Additionally, some teachers are unaware that roadway slopes are intentionally designed at specific angles for stability. Through Module 2, they gain a clearer understanding of the connection between friction on inclined surfaces and slope stability in real-world engineering applications.

2.4 Module 3 – Particle Size Analysis

2.4.1 Background

K-12 math teachers often receive questions from students about when logarithmic functions are used and what their real-life applications are. Module 3 addresses this by demonstrating how logarithmic functions are used in geotechnical engineering, specifically in particle size analysis. Participants are given sieve analysis results and asked to plot the particle size distribution curve on two types of graph templates: one using a linear scale and the other using a semi-logarithmic scale. Table 3 outlines the TEKS criteria that Module 3 aims to cover.

Table 3. TEKS (Texas Essential Knowledge and Skills) that can be taught through Module 3

TEKS for Mathematics	TEKS for Science
[Precalculus, (2) Functions] (I) determine and analyze the key features of exponential, logarithmic, rational, polynomial, power, trigonometric, inverse trigonometric, and piecewise defined functions, including step functions such as domain, range, symmetry, relative maximum, relative minimum, zeros, asymptotes, and intervals over which the function is increasing or decreasing. [Precalculus, (2) Functions] (N) analyze situations modeled by functions, including exponential, logarithmic, rational, polynomial, and power functions, to solve real-world problems. [Precalculus, (5) Algebraic reasoning] (G) use the properties of logarithms to evaluate or transform logarithmic expressions.	[Physics, (1) Scientific and engineering practices] (B) apply scientific practices to plan and conduct descriptive, comparative, and experimental investigations, and use engineering practices to design solutions to problems. - Physics, (1) Scientific and engineering practices] (F) organize quantitative and qualitative data using bar charts, line graphs, scatter plots, data tables, labeled diagrams, and conceptual mathematical relationships. [Physics, (2) Scientific and engineering practices] (A) identify advantages and limitations of models such as their size, scale, properties, and material.

2.4.2 Instruction

The instructional approach for Module 3 is presented below:

- Present photos of sand and clay particles magnified by a scanning electron microscope (SEM), emphasizing the vast difference in size between clay and sand particles.
- Explain to participants that soils typically consist of a range of particle sizes, and the distribution of these particles is determined through sieve analysis.
- Describe the process of sieve analysis and how the percent passing is calculated.
- Present the sieve analysis results and ask participants to calculate the percent passing as shown in Table 4.

Table 4. Results from sieve analysis used in Module 3

Particle size (mm)	Mass of soils retained on each sieve (g)	Mass of soils passing each sieve (g)	Percent passing each sieve (%)
75	0	1450	100 (= 1450/1450)
4.75	145	1305	90 (= 1305/1450)
2.00	261	1044	72 (= 1044/1450)
0.425	580	464	32 (= 464/1450)
0.075	319	145	10 (= 145/1450)
Pan	145	0	0

- Provide participants with the two graph templates. Explain that one template uses a linear scale for both x and y axes, while the other uses a semi-logarithmic scale, where the y axis is linear and the x axis is logarithmic with base of 10.
- Ask participants to plot the sieve analysis results on both templates. Instruct them to connect each data point with a straight line and determine the particle size corresponding to 20% passing (see Figs. 5(a) and 5(b)).

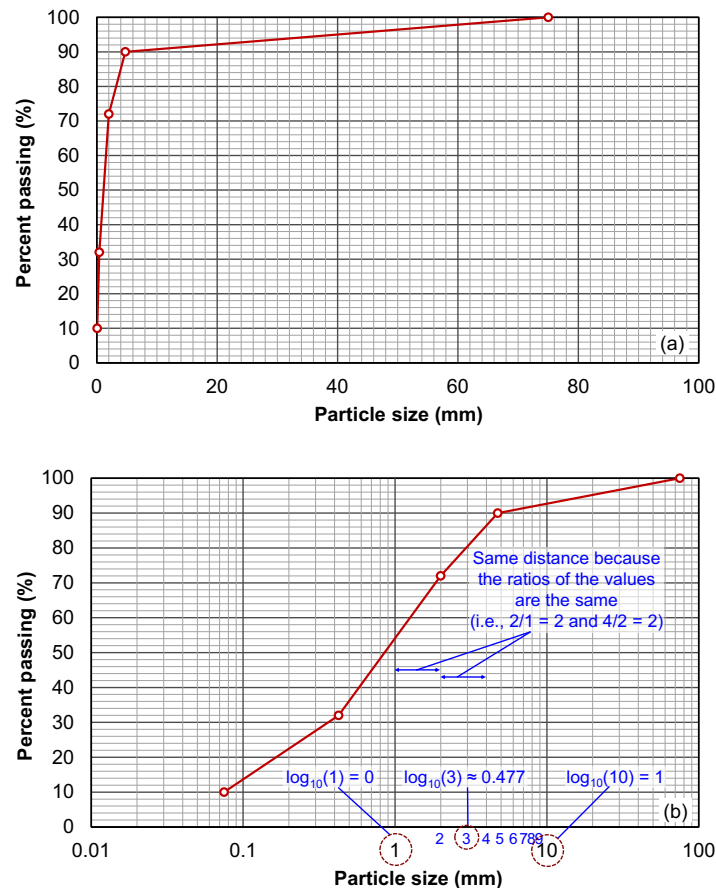


Figure 5. Particle size distribution curves plotted on (a) linear scale template and (b) semi-logarithmic scale template in Module 3

- (g) Lead a discussion about what challenges participants faced while plotting the particle size distribution curves and determining the particle size for 20% passing. Ask which template they thought was more effective when dealing with data that spans a wide range of magnitudes.
- (h) Draw participants' attention to the differences between the major vertical gridlines in both templates. Explain that in the linear scale template (Fig. 5(a)), the distance between the two neighbouring major vertical gridlines represents the increment (i.e., increments of 20, such as 0, 20, 40, 60, and 100).
- (i) Now focus on the semi-logarithmic scale template (Fig. 5(b)). Explain that the distance between two neighbouring major vertical gridlines does not represent a constant increment. Ask participants to identify the pattern in the equally spaced values (i.e., 0.01, 0.1, 1, 10, and 100). Wait for someone to recognize that the values correspond to powers of 10 (i.e., 10^{-2} , 10^{-1} , 10^0 , 10^1 , and 10^2).
- (j) Guide participants' attention to the minor vertical gridlines. Explain that in the linear scale, the minor vertical gridlines are evenly spaced, but in the semi-logarithmic scale, they are not. Clarify that the distance between two consecutive minor vertical gridlines in the semi-logarithmic scale depends on the ratio of the corresponding values, not the difference. For example, the distance between the minor gridlines representing 1 and 2 is the same as the distance between 2 and 4, because these number pairs have the same ratio of 2 (see Fig. 5(b)). On the other hand, the distance between 2 and 3 will be smaller than that between 1 and 2, since the ratio $3/2 (= 1.5)$ is smaller than $2/1 (= 2)$. Similarly, the distance between 3 and 4 will be smaller than the previous distance because $4/3 = 1.33$. Emphasize that as the value on the minor gridlines increases, the ratio of the consecutive values decreases, which explains why the distance between consecutive minor gridlines becomes smaller.

2.4.2 Reflections

Plotting particle size distribution curve on both graph templates help participants grasp the effectiveness of a logarithmic scale when handling data with a wide range of magnitudes. Some participants may ask how to determine the precise location of minor gridlines for specific values. For instance, in Fig. 5(b),

the minor gridline for 3 is about halfway between 1 and 10, rather than one-third of the way, as one might intuitively assume. To reinforce the concept of logarithmic scaling, it is helpful to explain that the location of minor gridlines is based on the logarithm of the value. For example, to determine the position of value 3 on a log scale, calculate $\log_{10}(3) \approx 0.477$. This means the gridline for value 3 is positioned roughly 47.7% of the way between 1 and 10 on the axis (see Fig. 5(b)). Similarly, for value 5, calculate $\log_{10}(5) \approx 0.699$. This places value 5 at approximately 69.9% (or about two-thirds) of the way between 1 and 10, rather than halfway. Providing this explanation helps participants develop a more intuitive understanding of how logarithmic scales function and reinforces the application of logarithms in real-world contexts.

3 Responses from K-12 Teachers and Preservice Teachers

The three learning modules developed in this study are well-positioned for integration into K-12 classrooms to facilitate student learning and stimulate interest in STEM disciplines. The lead author of the paper introduced these modules in a professional development workshop for in-service K-12 STEM teachers across West Texas. The workshop, titled *Transportation Engineering in the Classroom*, was a two-day event held on June 12-13, 2019. The three modules were introduced on Day 2. There were 12 attendees, including 11 STEM teachers (Grades 6-12) and one gifted education teacher (Grades 2-8). At the end of Day 2, a workshop evaluation survey was conducted, with 11 attendees responding. All 11 attendees indicated that 'Content presented was applicable to my subject/grade level' and that 'I gained one or more specific ideas that I can implement in my classroom'. Examples of evaluation comments from the workshop attendees are presented below:

- "The content was very interesting and unique. This is a workshop with content that is not often covered but is everyday real work content that we can relate to students."
- "I got great ideas to take back to classroom and can transform instruction."
- "Very informative. Wide range of topics within a topic. Best workshop I've attended in a long time. Especially enjoyed demonstration and hands on activities on Day 2 GeoTech."
- "I got great ideas to implement in various areas of science and math."
- "I think the content could be used across multiple content areas and I think students would benefit from real-world applications."

Furthermore, the second author of this paper incorporated these modules in College of Education undergraduate course, EDML 4375: Integrated Mathematics and Science Methods, for preservice secondary teachers. The Fall 2021 class included eight mathematics teachers and four science teachers. A survey was conducted on the effectiveness of the modules on potential applicability in K-12 STEM classrooms by asking "Do you think you gained one or more specific ideas that you can implement in your classroom?" On 7-point Likert Scale, 77.7% of students indicated 5 or above (5: Somewhat agree = 22.2%, 6: Agree = 33.3%, and 7: Strongly agree = 22.2%). Examples of feedback from preservice teachers are presented below:

- "My class deals with Friction Force, so the demonstration done was something that I can absolutely use."
- "The Sliding Cup was very interactive and had the class excited. A live example of how a concept works in the real world would be a good idea."
- "I can give the trigonometry examples from the friction model on an inclined plane."

To summarize, both in-service and preservice K-12 STEM teachers engaged with the modules through the workshop and coursework. The positive reception from both groups highlights their effectiveness in introducing geotechnical engineering into K-12 education. This dual perspective—from experienced teachers and future educators—provides valuable insight into the modules' impact. The next step is to provide coaching and support for secondary math and science teachers to develop their own integrated lesson plans, reinforcing connections between mathematics, science, technology, and geotechnical engineering.

4 Conclusions

This paper presented a case study in which three learning modules related to geotechnical engineering were developed and introduced to K-12 in-service teachers through a professional development workshop and to preservice teachers through coursework. The modules focus on connecting K-12 STEM topics to geotechnical engineering through active learning and providing clear real-world applications. Feedback from both in-service and preservice teachers indicated that the three learning modules align well with K-12 curriculum. Additionally, most participants reported gaining new ideas to implement in their classroom and enhance their instruction. These modules have great potentials for K-12 teachers to adapt and integrate into their classrooms, helping students better understand key concepts in science and mathematics while demonstrating real-world applications through the lens of geotechnical engineering.

References

- Ajmera, B., Crary, S. L., Wenaas, R., Wold, J., Stone, M., Jorgenson, T. (2024). Geotechnical Engineering Curriculum Modules for High School Math and Science Classes. *Proceedings of Geo-Congress 2024*, pp. 366-376
- Fiegel, G. L., Elia, V., Griffith, M. (2000). Geotechnical Engineering for Elementary School Students. *Proceedings of GeoDenver 2000*, pp. 26-38
- Margot, K. C., Kettler, T. (2019). Teachers' Perception of STEM Integration and Education: A Systematic Literature Review. *International Journal of STEM Education*, 6(2), pp. 1-16
- Osborne, J., Simon, S., Collins, S. (2010). Attitudes Towards Science: A Review of the Literature and Its Implications. *International Journal of Science Education*, 25(9), pp. 1049-1079.
- Raymond, A. J., Bronner, C. E. (2020). Integrating Geotechnical Engineering Research into K-12 Education through a Graduate Course in Engineering Education. *Proceedings of Geo-Congress 2020*, pp. 685-693
- Suescun-Florez, E. A., Cain, R. F., Kapila, V., Iskander, M. G. (2013). Bringing Soil Mechanics to Elementary Schools, *Proceedings of 2013 ASCE Annual Conference & Exposition*, pp. 23.254.1-23.254.18

Authors' bios

Hoyoung Seo, Texas Tech University (USA)

Dr. Hoyoung Seo is an associate professor at Texas Tech University who specializes in the field of Geotechnical Engineering. He holds his Ph.D. degree in Civil Engineering from Purdue University. His disciplinary research interests involve the design and analysis of foundations and development of climate-adaptive infrastructure. He received First Runner-Up Award from Deep Foundations Institute (DFI) in 2017 DFI Educational Trust Young Professor Paper Competition and is a member of ASCE Deep Foundations Committee. Dr. Seo has strong passion for teaching and was awarded multiple teaching awards from Texas Tech University for his dedication to teaching. He is also interested in engineering education and is the recipient of 2023 Best Case Study Award (Runner Up) from ASCE Journal of Civil Engineering Education.

Minju Yi, Texas Tech University (USA)

Dr. Minju Yi is an assistant professor of practice in the Teacher Education Department at Texas Tech University, where she earned her Ph.D. with a specialization in Teacher Education and Curriculum Studies. Her research focuses on (1) mathematics teacher education, (2) the integration of STEM content into teacher development, and (3) teacher evaluation systems and policies. Prior to her academic career, Dr. Yi was a public-school math teacher in Seoul, Korea. She is deeply passionate about working with student teachers, many of whom are first-generation college students from diverse

communities across Texas. As a first-generation college graduate herself, Dr. Yi finds it especially rewarding to help her students develop strong content knowledge and effective pedagogy in mathematics, empowering them to better support diverse K-12 students both within their communities and beyond.

An industry perspective of geotechnical engineering education and a learning approach by Tony Gee LLP

C.H. Shields, T.Y. Yap, C.T. Toms & T. Chalmers

Tony Gee LLP, Esher, UK

hiliary.shields@tonygee.com, yee.yap@tonygee.com, cyrus.toms@tonygee.com,
tarryn.chalmers@tonygee.com

ABSTRACT: Students graduate into the industry with a grounding in the principles of Geotechnical Engineering. For engineering professionals further learning and technical mentorship is vital to apply this knowledge into the real world. This paper reviews the current view of the industry and the efforts of the industry on education. Tony Gee, a UK civil engineering design consultancy has set up a Geotechnics' Academy to stimulate and encourage learning and knowledge share at all career levels. The paper recommends that: a structured learning path is needed to enable geotechnical engineers to develop in their careers; a roadmap is developed of the coordinated efforts of industry organisations, training organisations and overseas organisations; and links with academia and industry are fostered through dissemination of research and input into academic course contents.

Keywords: Technical Development, Industry, Knowledge Share

1 Introduction

Geotechnical research around the world continues apace, with continual advances in understanding, testing and measuring techniques and design methodologies. Meanwhile, the fundamental knowledge required for a geotechnical engineer that informs an understanding of how a soil is expected to behave and interact with a structure remains key. At undergraduate level, geotechnical engineering is taught as a part of a wider Engineering course and many within the industry do not undertake a specialist Masters course. Even when people have undertaken a Masters, the learning that comes with experience is vital and as an industry our aim must be for engineers to develop with a sound understanding of how fundamental learning is applied in practice.

The field of geotechnics has expanded due to focus on sustainability, expansion of capabilities and availability of numerical modelling software, automation and data capture, and due to the emergence and growth of new fields such as offshore wind and tailings dams. Around the world there are vibrant organisations who are seeking to advance and disseminate geotechnical knowledge. This relies on collective effort as with busy jobs it is hard for practitioners to follow developments. An overall picture that captures the various components and how they are connected would therefore assist.

To address these issues, Tony Gee has introduced several strands to geotechnical learning and development, which we have incorporated into our "Geotechnics' Academy". We have compiled a list of core skills of a geotechnical engineer, recognising also the many specialisms. This is helpful to an individual to measure their development as a geotechnical engineer and to understand how the many aspects of our field are inter-related. Through dedicated learning sessions covering both core and specialist fields we are encouraging ongoing learning and dissemination of in-house knowledge. In relation to numerical modelling, an ever-evolving field, we are ensuring that staff understand the soil models they are using and the limitations of the software. We also identify our research needs on an ongoing basis and work with universities and other organisations to stay up to date.

In summary, alongside the need to advance worldwide geotechnical knowledge and understanding, there is an equal need to keep educating geotechnical practitioners and pass on research knowledge in a tangible way. We consider our approach and methods at Tony Gee are worth sharing to stimulate discussion on how academia can help organisations such as ours to both build core skills and keep pace with developments. Suggestions are also made on ways forward to link education efforts in Academia and Industry, plus additional course content.

2 The current situation in industry

Students gain a sound grounding in soil mechanics and geotechnical engineering at undergraduate level, and more so at Masters level. In general they will not have the experience to see that learning fully in context. They need to build on that knowledge in their jobs or it becomes unused and forgotten.

Graduates are embarking on a learning path for a lifetime. We need them to grow alongside other engineers around them. Passing on experience is therefore key.

In general as a specialism within civil engineering we don't have structured learning paths. It has always been the case that geotechnical engineers learn through their work and the experience of their leaders. There are not further exams or marks of progression as in some other professions, other than achieving professional chartered engineer status. The steps to gaining that status are broadly defined so as to encompass all areas of civil engineering and there is no discipline-specific qualification for a chartered geotechnical engineer. But the way engineers work has changed. We work on computers, we have the internet at hand, we meet remotely in meetings, we work remotely and flexibly, we have many software tools, we use social media, and we need to embrace the growth of AI. Our field has expanded and graduates need to quickly acquire wider skills, for instance in sustainability, numerical modelling, data management, automation, visual tools, and project management. There is also a pressure to progress fast and increase in responsibility and salary (not least because education is expensive). In the past we as an industry have done a lot of work developing correlations for soil parameters from laboratory and insitu testing and back-analysis of structures. Experienced engineers know where these correlations came from, but recent engineers may not have that appreciation. Geotechnical engineering is not a prescribed process; it relies on understanding and judgement. Many of these concerns are echoed in Nikolic (2025).

The result is that it is difficult for a young engineer to measure their progress as a geotechnical engineer.

Possibly more than ever, guiding and encouraging our developing engineers in the ways to use the fundamental knowledge learnt at university is key. As is enabling them to build on that fundamental knowledge and grow into competent geotechnical engineers, able to apply scientific learning to solve real-world challenges is essential. In addition, with the now widespread use of numerical software and models, it is vital that engineers understand the basis of the models they are using, the limitations of the software and what they expect as results.

In parallel there is a need to help developing engineers understand what our field encompasses; where they sit within the vast spectrum and the opportunities that it provides. This includes the relationship to and interaction with other disciplines in ground engineering, for instance environmental geotechnics, geologists and earth sciences. We also need to help them recognise that, armed with the right tools, they have the ability to be versatile and an initial career path direction need not limit a future direction as they chart their geotechnical path through life.

Examples of the current breadth and diversity of our field include (far from exhaustive): The many traditional geotechnical engineering areas - desk study, ground investigation, soil mechanics, hydrogeology, foundations, retaining walls, slopes, earthworks etc; Carbon assessment and sustainability; Nature-based solutions; Effects of climate change/ resilience on geotechnical structures and ground conditions; Modern codes, e.g. second generation Eurocodes; Statistical analysis, e.g. stochastic and Monte Carlo methods; Widespread use and development of FE models; Progress on understanding and modelling of particulate behaviour; Advances in understanding behaviour of unsaturated soils; Geothermal applications; Foundation reuse; Advances in monitoring capability and remote sensing; New foundation types, e.g. offshore monopiles; Digital twins and data management; Processing large data sets and 3D modelling capabilities.

Academia is commendably striding forward on key research areas, being able to develop previous research findings and hypotheses through the use of sophisticated numerical analyses to address

industry / world needs. But this broadening of the industry is meaning that it is a challenge for the average practising engineer to keep up with published papers and conferences, which is exacerbated by pressures brought about by busy working lives.

3 The efforts of Industry on Education

Geotechnical organisations across our industry recognise the difficulties facing our community as the breadth of our field has grown and the way we work has changed. Examples of ongoing efforts to help advance and disseminate geotechnical knowledge to improve geotechnical practice and wider understanding of our role are given below.

Table 1. Examples of ongoing effort from UK organisations and with UK participation

Organisations (examples, not exhaustive)	Examples of input to education within the Industry
UK Non-profit making organisations	
The Association of Geotechnical Specialists (AGS)	The AGS (https://www.ags.org.uk/) was established to improve the profile and quality of geotechnical and geoenvironmental engineering. They have ten working groups and produce numerous guides, publications, conferences and webinars
The British Geotechnical Association (BGA) and Early Careers Group (BGA ECG)	The BGA (https://www.britishgeotech.org/) are the principal association for geotechnical engineers in the United Kingdom. They organise regular technical discussion meetings relevant to ground engineering, conferences and knowledge share.
The Institution of Civil Engineers (ICE) and ICE/ Emerald Publishing	The ICE (https://www.ice.org.uk/) organises regular meetings and supports key publications. In recent years they have arranged for the compilation of the Manual of Geotechnical Engineering (MOGE) which includes a 100 chapters giving guidance on investigation, design and implementation across the vast range of our field.
Construction Industry Research and Information Association (CIRIA)	CIRIA (https://www.ciria.org/) has produced numerous key guidance documents related to geotechnical design and construction, written by groups of experts.
The Federation of Piling Specialists (FPS) and early career group	The FPS (https://www.fps.org.uk/) is dedicated to improving standards, safety, working conditions and commercial practices within the industry. They are currently participating with the EFC in providing guidance on sustainability and the circular economy.
The British Drilling Association (BDA).	The BDA (https://www.britishdrillingassociation.co.uk/) provides guidance and qualifications to the people involved in the geotechnical drilling industry.
The Ground Forum and the Register of Ground Engineering Professionals (ROGEP).	The Ground Forum (https://ground-forum.org.uk/) is the 'umbrella' body for the ground engineering sector. It is also responsible for The Register of Ground Engineering Professionals (RoGEP), introduced in 2011. The Ground Forum also runs an Undergraduate Mentoring Programme with industry professionals.
The British Geological Survey (BGS).	The BGS (https://www.bgs.ac.uk/) holds numerous datasets, many freely available to the public and facilitates availability of geotechnical and geological data across the UK.
The Engineering Group of the Geological Society (EGGS)	The EGGS (https://www.geolsoc.org.uk/science-and-policy/specialist-groups/engineering-group/) organises technical meetings and sets up working parties leading to a range of Special Publications and technical handbooks.
Universities	UK Universities are undertaking research, alongside international connections, and liaising with industry for support and collaboration. Facilities include national centres for research at 14 universities as part of the UK Collaboratorium for Research in Infrastructure and Cities (UKCRIC https://www.ukcric.com/).
Other UK organisations	
Equipe Group	Equipe Group (https://www.equipegroup.com/) runs vocational courses to provide key through to advanced skills for drillers, undergraduates, technicians, earth scientists, geologists and engineers to start or progress their careers in drilling and geotechnics.

Ground Investigation Companies	Ground investigation companies have been hosting tours of their facilities and demonstrations to early career geotechnical engineers to help them understand the practicalities of the techniques and tests they are specifying
Engineering Software Companies	Software companies have been hosting webinars to help young engineers to understand the capabilities and applications to the software (e.g. Bentley).
Industry journals and magazines	e.g. Ground Engineering Magazine (https://www.geplus.co.uk/) runs several conferences throughout the year, together with publication of technical articles, current viewpoints and initiatives, and project news, to encompass the breadth of our industry.
Major Projects Learning Legacy	In recent years Major Projects in the UK, e.g. Crossrail which is a major new rail route crossing east to west across London, and High Speed 2 (HS2) which is a new high speed railway from London towards the Birmingham, have sought to compile the written findings from design and observation into a public database https://learninglegacy.crossrail.co.uk/ and https://www.hs2.org.uk/building-hs2/learning-legacy/ .
Examples from Overseas Organisations that UK has representative in	
The International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) and Young Members Group (YMPG)	The ISSMGE (https://www.issmge.org/) continues in its huge efforts in our field, with numerous committees across widespread topics, and providing access to educational resources including publications and webinars. The recent professional networking platform Geoworld makes the ISSMGE inclusive and accessible to all. The recent Heritage Time Capsule (HTC) Project has been launched.
Deep Foundations Institute (DFI) and DFI Europe	The DFI (https://dfi.org/) has numerous committees and publications and organises many webinars and conferences throughout the year.
European Federation of Foundation Contractors (EFFC)	The EFFC (https://www.effc.org/) aims to improve the standard of workmanship, technical competence, safety and innovation for specialist foundation contractors across Europe, through working groups, guidance documents and webinars.

Both Academia and Industry recognise the importance of working together. Most of the organisations listed in Table 1 involve representatives from both Academia and Industry in achieving their guidance. Universities work hard to reach out to industry for support and funding for collaborative research. Organisations within industry are aware of the importance of attracting and retaining students to go on to work in the industry and are keen to provide ideas and support for student dissertations. Major examples (amongst many) of successful joint collaborative research projects, which have been widely disseminated include:

- The collaboration between Imperial College and several industry organisations on advancing understanding of driven pile design in clays, sands and weak rocks, e.g. Jardine et al. (2015).
- The Pile Soil Analysis (PISA) project to advance understanding of design of offshore monopiles with short length/diameter ratio, involving multiple universities and industry organisations, e.g. Byrne et al. (2017).
- Research by universities in the USA and Europe (e.g. Cambridge University, Swansea University, Technical University of Munich, Missouri University of Science and Technology amongst others) in collaboration with several industry organisations within DFI and the EFFC, which have led to the production of the EFFC/DFI Guide to Tremie Concrete for Deep Foundations, e.g. Beckhaus (2024).

In summary there is a huge ongoing effort in the UK and worldwide. It would be helpful to have a country-specific coordinated picture of all the efforts and linking in with key overseas organisations. Then in any one area it could be easily understood what the current efforts are in education, research and dissemination.

4 Tony Gee Geotechnics' Academy

To help stimulate and encourage geotechnical learning and knowledge share for both our developing engineers and our more senior staff, Tony Gee has introduced several strands to geotechnical learning and development, which we have incorporated into our "Geotechnics' Academy". We describe this below

to give an example of what can be achieved within industry to support our geotechnical engineers; other organisations are developing similar approaches.

The learning and development programme follows the philosophy of John Burland's Geotechnical Triangle, first introduced in his Nash Lecture, (Burland, 1987) and reproduced in Figure 1. The aim is to clearly impart the importance of:

- a sound understanding of ground conditions and their origin,
- understanding soil behaviour and the basis for empirical correlations
- understanding the basis of our models, both traditional and numerical
- experience as a geotechnical engineer, tying all these strands together

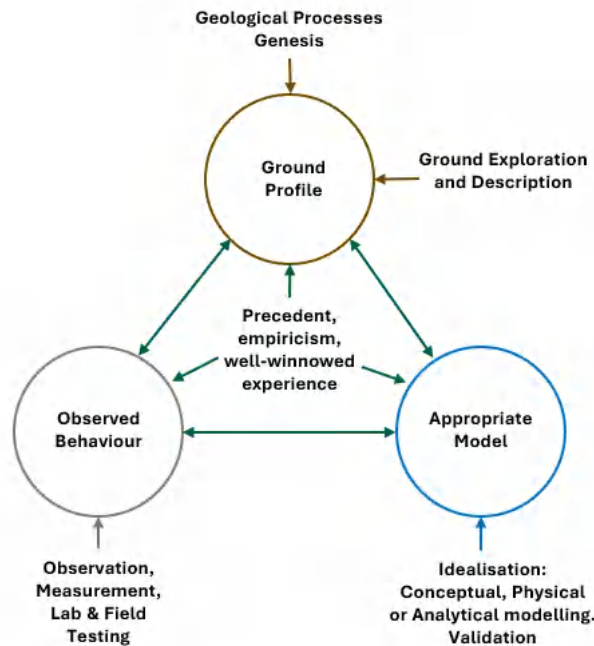


Figure 1. The Geotechnical Triangle by John Burland, adapted from Burland (2008)

The programme aims:

- to encompass the typical range of skills of a geotechnical engineer,
- to facilitate access to corresponding guidance/ information resources,
- to stimulate technical learning and discussion,
- to join up our experience, research and development,
- to identify gaps in training and experience to enable the company to work more effectively.

The building blocks of the programme encompass six core areas:

1) Geotechnical learning objectives pre-chartership

A list of core skills of a geotechnical engineer, recognising also the many specialisms has been compiled. This is aligned with Knowledge, Experience and Ability as defined in the attributes required for becoming a Chartered Civil Engineer in the UK, under the supervision of a Delegated Engineer (DE) and Supervising Civil Engineer (SCE). This helps an individual measure their development as a geotechnical engineer and to understand how the many aspects of our field are inter-related. These have been grouped into five categories (Table 2):

- Desk study and site investigation
- Geotechnical Design – core skills
- Geotechnical implementation, practical considerations/ specification
- Geotechnical analysis – linked skills, e.g. FE, digital, carbon, research

- Geotechnical analysis specialist fields, e.g. tunnelling, seismic, dams, mining
- Construction supervision

Staff record individual progress in the field of Geotechnics against the categories in alignment with the ICE attributes.

Table 2. Geotechnical Learning Objectives up to Chartered Engineer Status

1 Desk Study and Site Investigation		K	E	A
Obtain knowledge (K) and experience (E) in all. Ability achievements (A) as discussed with Delegated Engineer/Supervising Civil Engineer.				
1.1	Desk Study			
1.2	Application of the relevant Health & Safety regulations in relation to ground investigation for your region			
1.3	Experience of ground investigation techniques, equipment and methods of working			
1.4	Use of the relevant ground investigation standards and codes of practice for your region			
1.5	The application of engineering geology to civil engineering works and particularly the origins and processes responsible for the deposition, erosion, conditioning and mechanisms for movement of soil and rock			
1.6	Scoping and specification of ground investigation works			
1.7	Supervision and checking of factual ground investigation data			
1.8	Specification and performance of in-situ testing techniques			
1.9	Specification, performance and scheduling of laboratory testing techniques			
1.10	Describe soil and rock according to the requirements and standards for your region			
1.11	Production of Interpretative report including recommendation for geotechnical design			
1.12	Have an awareness of recent developments in new ground investigation techniques			
2 Geotechnical Design				
2.1 Geotechnical Design – Core Skills		K	E	A
Obtain knowledge in 9 of the following, experience in 6. Ability achievements as discussed with DE/SCE.				
2.1.1	Selection of relevant design parameters			
2.1.2	Design of shallow foundations – bearing capacity and settlement. Examples include: drained/ undrained, soft clay/ stiff clay/ granular etc			
2.1.3	Design of piled foundations for vertical load – Examples include: bored (with/ without support fluid), driven closed ended, driven open ended, etc			
2.1.4	Design of piles for lateral load – Examples include cohesive, granular material, etc			
2.1.5	Pile group analysis – vertical load – bearing capacity and settlement			
2.1.6	Pile group analysis – lateral load – structural effects and movements			
2.1.7	Design of gravity earth retaining structures – Examples: concrete, gabion etc			
2.1.8	Design of embedded retaining structures – Examples: secant wall, contig wall, sheet pile wall			
2.1.9	Slope stability analysis – Examples: cohesive, granular, embankment, cutting etc			
2.1.10	Ground movement assessment - Examples include, building damage assessment, tunnels, utilities etc			
2.1.11	Assessment of consolidation and creep settlements			
2.1.12	Underpinning			
2.1.13	Ground anchors			
2.2 Geotechnical implementation, practical considerations/ specification				
Obtain knowledge in 6 of the following, and experience in 3 of the following. Ability achievements as discussed with DE/SCE.				
2.2.1	Foundation Reuse			

2.2.2	Constructability/ temporary works considerations			
2.2.3	Piling specification			
2.2.4	Earthworks			
2.2.5	Reinforced earth			
2.2.6	Groundwater control			
2.2.7	Ground improvement			
2.2.8	Monitoring			
2.3 Geotechnical analysis – linked skills		K	E	A
Obtain knowledge in all of the following, and experience in 2. Ability achievements as discussed with DE/SCE.				
2.3.1	FE analysis or review skills			
2.3.2	Digital skills			
2.3.3	Carbon analysis			
2.3.4	Ongoing geotechnical research developments			
2.4 Geotechnical analysis specialist fields		K	E	A
May be substituted for one of the experience core skills as specialist path				
2.4.1	Tunnelling			
2.4.2	Seismic analysis			
2.4.3	Dams			
2.4.4	Mining			
3 Construction Supervision		K	E	A
Obtain knowledge in all of the following, and experience in 1. Ability achievements as discussed with DE/SCE.				
3.1	Site investigation supervision			
3.2	Piling supervision			
3.3	Earthworks supervision			
3.4	(to be completed by individual)			
3.5	(to be completed by individual)			

2) Geotechnical design themed talks and discussions

Through dedicated learning sessions covering both core and specialist fields we are encouraging ongoing learning and dissemination of in-house knowledge.

A programme of monthly themes has been developed covering a considered list of core geotechnical knowledge (Table 3). Each theme is addressed in typically two recorded sessions with presentations and discussion, including contributions of related experience. The programme is structured so that themes follow a logical order and allow the extension of all staff's knowledge across the career structure. References are compiled for each topic. The themes recap on core geotechnical learning as described for instance by Atkinson (2016) and extend them into industry practice. Examples of content and references are shown in Table A1 in the Appendix (for axially loaded piles). The sessions are held in person and online; some examples are given in Figure 2.

Tony Gee have a series of Technical Notes covering many aspects of geotechnical design. These are being curated with the monthly themes.

In relation to numerical modelling, which is an ever-evolving field, we are ensuring that staff understand the constitutive soil models they are using and the limitations of the software. Young engineers are encouraged to set up the numerical models themselves (following the checklists described in CIRIA C791, O'Brien and Higgins (2020)) to gain hands-on experience, and compare the findings of numerical models with simple hand calculations. Should any discrepancies arise, they can engage with experienced users to discuss and interrogate the models, ensuring that no details are over-looked. New users will also perform a benchmark exercise similar to that of Schweiger (2002) to highlight that numerical analyses are very sensitive not only to constitutive soil model and material properties but also to modelling and implementation details.

Table 3. Geotechnical Learning and Discussions Sessions – List of Topics

Ground Profile (geological processes, ground exploration and description)
Desk Study/ Ground Risk
Geology
Specification of field GI exploratory hole and insitu test techniques
Specification and interpretation of laboratory tests
Groundwater
Geotechnical data capture
Contaminated land
Soil Behaviour (measurement, lab and field testing, observation)
Angle of friction and dilation in granular materials
Undrained behaviour of clays – theory, real soil behaviour, measurement and characterisation.
Variation of stiffness with strain level and stiffness correlations for foundation design.
Behaviour of partly saturated soils
Heave pressure
Behaviour under cyclic load
Seismic design
Geotechnical design model (conceptual, physical or analytical modelling)
Finite Element Analysis – modelling soil behaviour and Quality Assurance
Seepage and dewatering.
Earth pressure. Theory and design of embedded retaining walls. Consideration of propping and ground anchors.
Bearing capacity and settlement. Elastic theory. Non-linear soil behaviour. Design shallow and raft foundations.
Theory and design of gravity retaining structures. Consideration of different types including reinforced earth.
Pile group behaviour – vertical and lateral. Limitations of elastic theory.
Slope stability
Embankments on soft Clays and ground improvement. Include consideration of weak fills.
Geotechnical design practice (Empiricism, semi-empiricism)
Pile design total stress approach in Clay soils
Pile design effective stress approach in Clay soils
Pile design in granular soils
Pile design in weak rocks
Laterally loaded piles
Tunnelling
Foundation Reuse
Theory and specification of earthworks
Geotechnical Design Criteria and Validation
Current FOS in Eurocodes and considerations of Second Generation Eurocodes
Sustainability
Monitoring and Remote monitoring

3) Review of Literature and Published Webinars

This includes presentation of a paper by a small group and review session, and group study of published webinars to encourage our engineers to be aware of published sources of learning and current thinking.

4) Dissemination of project experience and external experience

Lunchtime talks on dissemination of project experience and from external industry speakers in geotechnical topic areas.

5) Research and development

Tony Gee invests heavily in research and development and run an in-house Programme for technology and innovation. The aim of the Programme is to promote and encourage research and development at all levels. Any staff member can apply for funding; each application is reviewed by a panel who assesses each application on the basis of its value to the business, clients and the industry as a whole. To help keep abreast of current thinking and developments we are also active on external committees and geotechnical research, publication bodies and universities, e.g. ICE, AGS, CIRIA, DFI, ISSMGE, Imperial College. Activities are being curated into an R&D Geotechnics area.

6) Professional development

To encourage early career geotechnical engineers to keep up with the ICE professional requirements, regular sessions are held to work on discussion of current industry topics, reporting and recording.

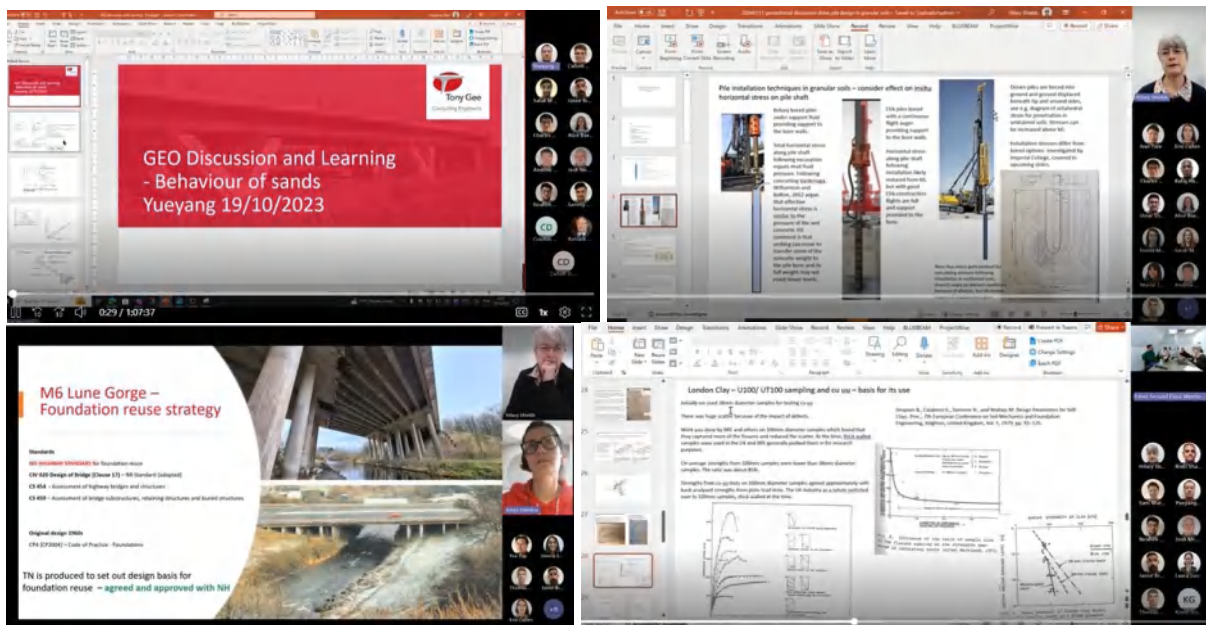


Figure 2. Examples from recording of different learning and discussions sessions

Tony Gee's geotechnical work spans a large variety of different types of geotechnical design, different ground conditions, different size projects and different length projects. Our geotechnical engineers need to be knowledgeable, versatile and able to adapt to different design situations. The Geotechnics' Academy helps to build and reinforce our skills. By maintaining and developing strong core skills, the academy also helps provide a versatile team of engineers able to service the recent and specialised areas that Tony Gee is involved in, Figure 3. In 2024 a survey was carried out internally across all offices on the benefits that staff saw from the academy. The feedback was very positive and gave confidence that the initiative was meeting its aims, as illustrated in Figure 4.

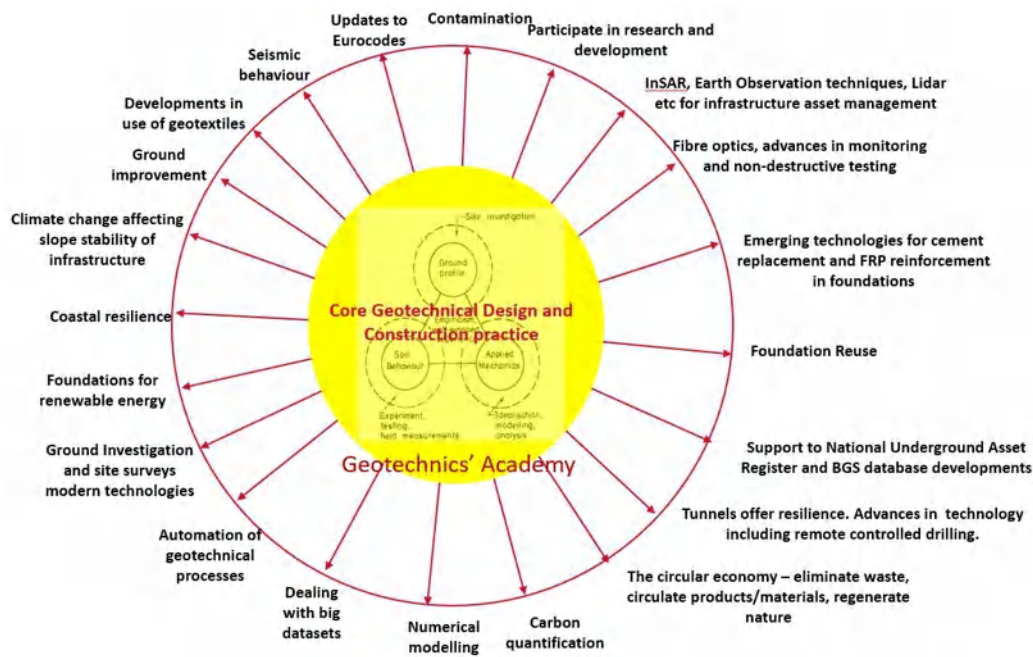


Figure 3. How the Academy helps to support not only the traditional geotechnical engineering but also the more recent and specialised areas.

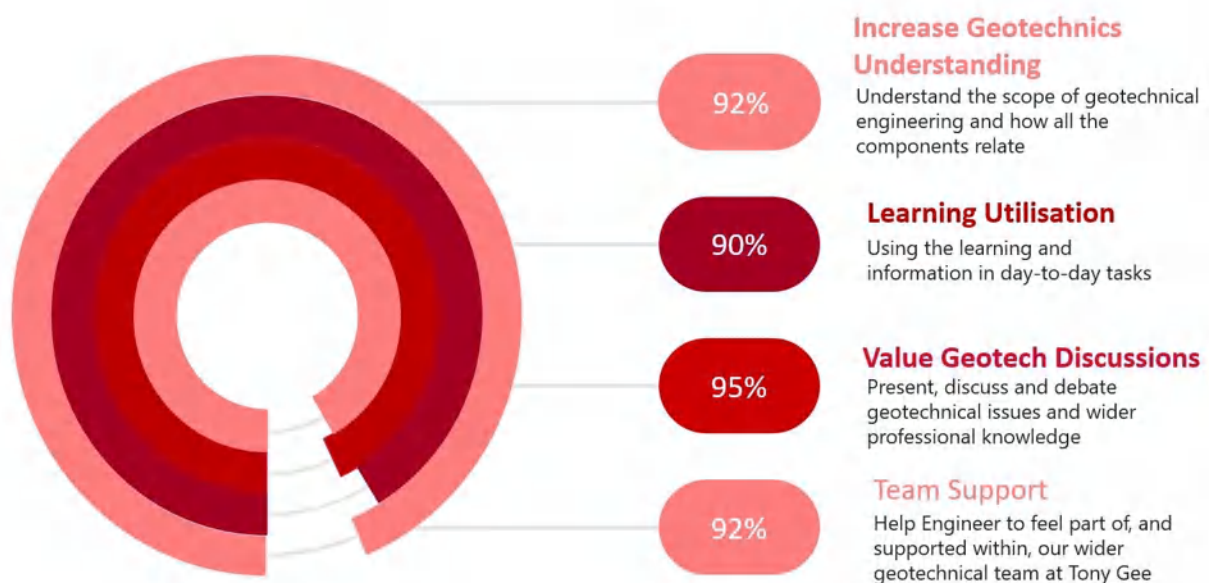


Figure 4. Feedback on the benefits of the academy from staff.

5 Suggestions for way forward to link educational efforts in academia and industry

This paper responds to the recent message from the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) TC-306: "On the occasion of the International Day of Education, January 24, the Technical Committee 306 on Geo-Engineering Education emphasizes the crucial role university education plays in advancing the state of knowledge within the geotechnical engineering field. In this day, we encourage all stakeholders in this community to support initiatives that promote access to quality education. This year's theme, "AI and education: Preserving human agency in a world of automation," specifically highlights the urgency and the importance of equipping individuals with

adequate knowledge to properly understand and influence rapidly evolving technological advancements. On this day, we encourage educators, students, and professionals to engage in collaborative efforts that may develop innovative teaching methods and overall enhance the geotechnical education state of practice. By fostering a deep understanding of soil mechanics and geotechnical engineering, future engineers are empowered to design and implement innovative solutions that ensure the safety and sustainability of engineering projects and to address complex challenges in today's rapidly changing environment."

Companies within industry depend on paid project work. Efforts on research and education are enabled through profits and commitment from staff. It is therefore difficult for smaller companies to support a major programme of in-house training and even for bigger companies, paid work often needs to take preference. A solution could be for universities to run programmes of fundamental learning culminating in dissemination of recent advances that can help organisations such as ours to both build core skills and keep pace with development. On the other hand, practitioners within the industry grapple with practical design and construction considerations and build up experience that goes beyond normal university education. Therefore, in turn, the industry can and does support universities through guest lectures, mentoring and industrial experience or placements. This helps students to be more informed about the extent of our industry and the nature of the work carried out in different areas across our field. It also fosters conversations between individuals within universities and industry and promotes sharing of ideas. With the advent of widespread communication through platforms like Teams or Zoom etc., it has become easier for practitioners to attend university learning sessions and for students to attend continuing professional development sessions within the Industry.

Such collaboration also helps industry to influence academic research so that it addresses project need challenges. For example, whilst Academia is progressing in developing advanced constitutive models to accurately replicate true soil and structural behaviour, the industry often relies on simpler constitutive models due to budget limitations, time constraints, and a lack of comprehensive soil testing data. Collaborative efforts on selected projects can help academia understand these industry challenges. In turn, this collaboration allows the industry to access the latest academic advancements and research. An example is the Pile Soil Analysis (PISA) project which investigates the interactions between soil conditions and monopiles. The developed design method is implemented in commercially available software PLAXIS monopile designer (Panagoulas et al., 2021), which can be used by practitioners.

An industrial placement year can provide students with invaluable hands-on work experience. This enables them to apply theoretical knowledge learned in their university courses and consider constructability from practical perspectives, deepening their understanding and reinforcing their learning.

A review of course content driven by an industry consultation exercise would also be of benefit. For instance, Instrumentation and Monitoring (I&M) would be an excellent addition to undergraduate courses. This is a broad field in itself and key to a sustainable future (e.g. Shields, 2025). At one end we have futuristic aspirations starting to happen now, for instance use of distributed fibre optic sensing to measure strain and temperature, use of interferometric synthetic aperture radar (InSAR) data to measure ground movement and changes in soil moisture content, use of Digital Twins to capture predicted and observed behaviour. At the other end we are often in the situation where it is difficult to get instrumentation installed at all, or it is not effectively planned, procured and documented/reviewed and the data may not be very useful. Incorporating I&M onto undergraduate courses would help raise awareness of its importance across all sectors of Civil Engineering. Another example is foundation (and superstructure) reuse which is an important area which has gained worldwide attention within industry, associated with de-carbonisation and also congestion beneath our cities. Construction sequencing and temporary works considerations associated with deep excavations would be another. There are clearly many examples.

A useful addition to undergraduate courses would be to prepare students to understand the breadth of the industry they are entering and the overlap of the different disciplines, so that they start out seeing the full picture and how it is all connected. The industry can help with this, as described above.

There is a need for better communication channels. Many practitioners don't manage to attend conferences, particularly those overseas. There is a potential need for the conferences be more coordinated and dissemination of the output to be improved. PhDs/dissertations at universities may never reach industry. There is a need for Academia and industry to consider ways to promote this knowledge and disseminate.

In addition to new research and developments there is much great work from the past with papers based on detailed observations of soil and foundation behaviour (very careful detailed papers by organisations such as BRE, TRRL, LCPC, DGI, NGI etc). This classic research of the past is still very relevant and in many instances issues looked at today were looked at in the past, but not necessarily known about. The ISSMGE Heritage Time Capsule project is a great initiative to try to ensure that historic research is carried forward into the future, as is Geoworld. More people need to know about these initiatives and feed into them.

It is suggested here that some form of live activity map could help all interested parties understand what each is doing and would form a starting point for better interaction.

6 Concluding Remarks

Students graduate into the industry with a grounding in the principles of Geotechnical Engineering. As engineering professionals further learning and technical mentorship is vital to apply this knowledge into the real world with empiricism, application of case history examples and well-winnowed experience. As the breath of the industry widens there is becoming a loss of focus on the technical expertise as focus shifts to other professional activities.

There are a number of organisations within the UK and worldwide with ambitions and good intentions to share knowledge, provide networking opportunities, disseminate experience, provide opportunities for collaboration and publicity. Academic research is expanding the understanding and developing models to replicating true soil and structural behaviour.

This paper identifies and suggests the following advances to develop the geotechnical profession:

- Provide a structured learning path for geotechnical engineers to develop in their careers.
- Provide a roadmap of the coordinated efforts of industry organisations, training organisations and overseas organisations linking the efforts of many practitioners and universities in promoting and advancing knowledge in the industry.
- Dissemination of academic research into industry. Collaboration on the challenges faced by industry.
- Industry consultation of academic course contents. Preparing students for the breath of the industry and cross over with different disciplines.

References

- Atkinson, J. (2016). Basic Geotechnical Engineering Skills What Can Graduates Do? First John Burland Lecture. ISSMGE.
- Burland, J.B. (1987). Nash Lecture: The teaching of soil mechanics – a personal view, Proc. 9th European Conference on Soil Mechanics and Foundation Engineering, Dublin, Ireland, Balkema, Rotterdam, Vol. 3: 1427–1447.
- Burland, J.B. (2008). Personal reflections on the teaching of soil mechanics. Proceedings of the 1st International Conference on Education and Training in the Geo-sciences, Constantza, Romania, June 2-4, Manoliu & Radulescu (eds.), pp. 35-48, CRC Press, Taylor & Francis, London, UK.
- Nikolic, A. (2025). The decline of engineering expertise – a crisis in the geotechnical sector. Ground Engineering Plus, 22 January.
- O'Brien, A. S., Higgins, K.G. (2020). The management of advanced numerical modelling in geotechnical engineering: good practice (C791). CIRIA.
- Panagoulas, S., Brinkgreve, R.B.J., Zampich, L. (2021). PLAXIS Monopile Designer CE V21 – Manual.
- Schweiger, F.H. (2002). Benchmarking in geotechnics 1. Graz: computational Geotechnics Group, Institute for Soil Mechanics and Foundation Engineering, Graz University of Technology.
- Shields, C.H. (2025). Monitoring is key to a sustainable future. Ground Engineering Plus, April.

Appendix

Table A1. Examples of Tony Gee Geotechnics' Academy topic content and references – for axially loaded piles

Topic	References
Pile capacity design total stress approach in Clay soils	
Overview of total stress design approach	Burland (1987); Burland and Cooke
What is happening to stresses in the ground when we load a pile	(1974); Cole and Patel. (1992); Hight et al. (2007); Karlsrud et al. (2005); Ladd and DeGroot (2004); LDSA (2017); Mayne and Kulhawy (1982); Poulos (1989); Randolph and Wroth (1979); Simpson et al (1979)
Historical basis for total stress approach	
Back-analysis of α in London Clay	
Examples of α in the literature – different soils and different pile types	
What is undrained shear strength and how do we measure it	
Pile capacity design effective stress approach in Clay soils	
What is the effective stress approach	Burland (1973); Burland (1990); Burland and Twine (1988); Finlay et al. (2001); Lehane et al (1994); Patel. (1992); Pellew. (2002); Simpsom et al. (1979); Skempton. (1959); Vardenega et al. (2012)
Effective stress approach in soft clay – driven piles	
Effective stress approach in OC clay – bored and driven piles	
Findings of Imperial College – driven piles	
Thinking about K_0	
Outline of effective stress pile calculation	
Pile capacity design in granular soils	
Pile resistance – shaft capacity and end bearing	Barker et al. (2010); Bell and Robinson (2012); Bolton (1986); Fleming et al (2009); Gavin et al. (2015); Green and Kightly (2005); Jardine et al. (1998); Jardine et al. (2005); Lambe and Whitman (1969); Lehane (1992); Niazi and Mayne (2013); Patel et al. (2015); Tavenas and Audy (1972); Tomlinson (1994); Yeats and O'Riordan (1989)
Effect of installation method	
Shaft resistance derivation: Bored piles and CFA piles; Driven piles; Driven piles Imperial College CPT approach	
End bearing derivation: Bearing capacity approach; Thanet sand piles; Driven piles – Imperial College CPT approach	
Group effects on driven piles and ageing effects	
Pile design in weak rocks	
Pile design in weak rocks – traditional approaches based on UCS	Alitalesh et al. (2015); Bowden et al. (1998); FPS (2004); Lord et al. (2002); Lord et al. (2002); Manceau et al. (2020); Gannon et al. (1999); Markvukaj et al (2023); Seidel and Collingwood (2001)
Theoretical considerations based on insitu stress and cavity expansion	
Very weak rocks, Mercia Mudstone, Chalk	
Pile group behaviour – vertical capacity and settlement	
Overview of pile group behaviour in comparison with single piles	Fleming (1992); Fleming et al (2009); O'Brien (2012); Randolph. (1994); Mandolini et al. (2005); Randolph and Reul (2019); Randolph and Wroth (1979); Tomlinson (1994); Whitaker (1979)
Pile group ultimate capacity, consideration of failure mechanisms	
Pile interaction and load distribution between piles, superposition	
Design guidance for pile sizing in groups	
Effect of non-linear soil stress strain behaviour on load distribution	
Case study of load taken to base of pile group	
Proximity of underlying weaker layer on pile group capacity	
Theory and methods for calculating settlement of a single pile	
Importance of case histories for measured load- settlement	
Influence on settlement of soil stiffness along shaft and below base	
Simplified methods of settlement analysis: pile group settlement ratio, elastic interaction factors, equivalent pier, equivalent raft	
Pile springs for structural analysis	

References in Table A1 for axially loaded piles

- Alitalesh, M., Mollaali, M., Yazdani, M. (2015). Correlation between uniaxial strength and point load index of rocks, Japanese Geotechnical Society Special Publication, 2(12):504-507.
- Barker, C., Niewiarowski, M., Patel, D.C. (2010). Central Saint Giles – Basement and foundations designed for future crossrail tunnelling, DFI-EFFC International Conference: Geotechnical Challenges in Urban Regeneration, London.
- Beckhaus, K., (2024). Tremie Concrete for special geotechnical works – a story about performance and sustainability, Proceedings of the XVIII ECSMGE.
- Bell, A. Robinson, C. (2012). Single Piles, Manual of Geotechnical Engineering Chapter 54, ICE Publishing.
- Bolton, M. D. (1986). A guide to soil mechanics, London: Macmillan.
- Bolton, M. D. (1986). The strength and dilatancy of sands. *Géotechnique* 36, No. 1., 65-78
- Bowden, A.J., Lamont-Black, J., Ulliyott, S. (1998). Point load testing of weak rocks with particular reference to Chalk, *Quarterly Journal of Engineering Geology*, 31, 95-103.
- Burland, J., Cooke, R.W. (1974). The design of bored piles in stiff clays. *Ground Engineering* V7, N4, July, 1974, pp. 28–35.
- Burland, J.B. (1973). Shaft friction of piles in clay – a simple fundamental approach, *Ground Engineering*, January, pp 30-42.
- Burland, J.B. (1990). On the compressibility and shear strength of natural clays. *Géotechnique* 40, No. 3, pp. 329-378.
- Burland, J.B., Twine, D. (1988). The shaft friction of bored piles in terms of effective strength, *Deep foundations on bored and auger piles*, Balkema.
- Byrne, B.W., McAdam, R.A., Burd, H.J., Houlby, G.T., Martin, C.M., Beuckelaers, W.J.A.P., Zdravkovic, L., Taborda, D.M.G., Potts, D.M., Jardine, R.J., Ushev, E., Liu, T., Abadias, D., Gavin, K., Igoe, D., Doherty, P., Skov Gretlund, J., Pacheco Andrade, M., Muir Wood, A., Schroeder, F.C., Turner, S., Plummer, L. (2017). PISA: New Design Methods for Offshore Wind Turbine Monopiles, 8th International Conference for Offshore Site Investigation and Geotechnics, London.
- Cole, K.W., Patel D.C. (1992). Review of prediction of pile performance in London Clay under the action of service loads. *Piling European practice and worldwide trends*.
- Federation of Piling Specialists, (2004). The design of bored piles in Chalk.
- Fleming, W. G. K. (1992). A new method for single pile settlement prediction and analysis, *Géotechnique* 42, No. 3, 411-425.
- Fleming, K., Weltman, A., Randolph, M., Elson, K. (2009), *Piling Engineering*, Taylor and Francis.
- Finlay, T.C.R., White, D.J., Bolton, M.D., Nagayama, T. (2001). Press-in piling: the installation of instrumented tubular steel piles with and without driving shoes, 5th International conference on deep foundation practice, Singapore, pp199-208.
- Gannon, J.A., Masterton, G.G.T., Wallace, W.A., Muir Wood, D. (1999). Piled foundations in weak rock, CIRIA.
- Gavin, K., Jardine, R.J., Karlsrud, K., Lehane, B. (2015). The effects of pile ageing on the shaft capacity of offshore piles in sand, *International Symposium Frontiers in Offshore Geotechnics*, Oslo, Volume 1.
- Green, T.A.L., Kightley, M.L. (2005). CAPWAP testing – theory and application. *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering*, Osaka, Japan, Sept. 12-16, Millpress Science Publishers/IOS Press.
- Hight, D.W., Gasparre, A., Nishimura, S., Minh, N.A., Jardine, R.J., Coop, M.R. (2007). Characteristics of the London Clay from the Terminal 5 site at Heathrow Airport, *Géotechnique* Volume 57 Issue 1, February 2007, pp. 3-18.

- Jardine, R.J., Merritt, A.S., Schroeder, F.C. (2015). The ICP Design Method and Application to a North Sea Offshore Wind Farm, IFCEE 2015 © ASCE 2015.
- Jardine, R.J., Overy, R.F., Chow, F.C. (1998). Axial capacity of offshore piles in dense North Sea sands. *Journal of Geotechnical and Geoenvironmental engineering*, ASCE, February 1998, pp 171-178.
- Jardine, R.J., Chow, F.C., Overy, R.F., Standing, J. (2005). ICP design methods for driven piles in sands and clays, Thomas Telford.
- Karlsrud, K., Clausen, C.J.F., Aas, P.M. (2005). Bearing capacity of driven piles in clay, the NGI approach. *International symposium on frontiers in offshore geotechnics*, pp. 775-782.
- Ladd, C.C., DeGroot, D.J. (2004). Recommended practice for soft ground characterisation, 12th Panamerican conference on soil mechanics and geotechnical engineering, Massachusetts Institute of Technology.
- Lambe, T.W., Whitman, R.V. (1969). *Soil mechanics*, John Wiley and Sons.
- Lehane, B.E. (1992). Experimental investigations of pile behaviour using instrumented field piles, PhD thesis, University of London.
- Lehane, B.E., Jardine, R.J., Bond, A.J., Chow, F.C. (1994). The development of shaft resistance on displacement piles in clay, XIII ICSMFE, New Delhi, India.
- London District Surveyors Association (LDSA), (2017). Guidance notes for the design of straight shafted bored piles in London Clay.
- Lord, J.A., Clayton, C. R.I., Mortimore, R.N. (2002). *Engineering in Chalk*, CIRIA C574.
- Manceau, S., Klapper, J., Jardine, R.J., Hall, A., Barbosa Moreira, P. (2020). The field behaviour of drilled and grouted piles in rock, *Piling 2020*, ICE Publishing.
- Mandolini, A., Risso, G., Viggiani, C. (2005). Pile foundations: Experimental investigations, analysis and design, *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering* © 2005–2006 Millpress Science Publishers/IOS Press.
- Markvukaj, S., Pye, S., Vance, M., O'Brien, A., Farooq, I. (2023). Shaft friction design for piles in extremely weak to weak Mercia Mudstone, *High Speed Two (HS2): Infrastructure Design and Construction (Volume 3)*, Thomas Telford Limited and High Speed Two 2023.
- Mayne, P.W., Kulhawy, F.H. (1982). K₀-OCR relationships in soil. *Journal of the Geotechnical Engineering Division*, Volume 108, Issue 6.
- Niazi, F.S., Mayne, P.W. (2013). Cone penetration test based direct methods for evaluating static axial capacity of single piles: a state of the art review, *Geotechnical and Geological Engineering*, August.
- O'Brien, S.A. (2012). Pile-group design. *Manual of Geotechnical Engineering* Ch 55, ICE.
- Patel, D., Glover, S., Chew, J., Austin, J. (2015). The Pinnacle – design and construction of large diameter deep base grouted piles in London, *Ground Engineering*, November.
- Patel, D.C., (1992). Interpretation of results of pile tests in London Clay, *Piling Europe*, ICE.
- Pellew, A. (2002). Field investigations into pile behaviour in Clay, PhD thesis, University of London.
- Poulos, H.G. (1989). Pile behaviour – theory and application. *Géotechnique* 39, No. 3, pp365-415.
- Randolph, M.F. (1994). Design methods for pile groups and piled rafts, XIII ICSMFE, 1994. New Delhi, India / XIII CIM STF, 1994. New Delhi. Inde.
- Randolph, M.F., Reul, O. (2019). Practical approaches for design of pile groups and piled rafts, 4th Bolivian International Conference on Deep Foundations.
- Randolph, M.F., Wroth, C.P. (1979). An analysis of the vertical deformation of pile group, *Géotechnique* 29, No.4, pp. 423-429.

- Seidel, J.P., Collingwood, B. (2001). A new socket roughness factor for prediction of rock socket shaft resistance, *Can. Geotech. J.* 38: 138–153.
- Simpson, B., Calabresi, G., Sommer, H., Wallays, M. (1979). Design parameters for stiff clays. *Proceedings of the 7th European Conference on Soil Mechanics and Geotechnical Engineering*, Brighton, Vol. 4, pp. 91–125
- Skempton A.W. (1959) Cast in-situ bored piles in London Clay, *Géotechnique* 9, No. 4, pp. 153–173
- Tavenas, F., Audy, R. (1972). Limitations of the Driving Formulas for Predicting the Bearing Capacities of Piles in Sand, *Canadian Geotechnical Journal*.
- Tomlison, M.J. (1994). *Pile Design and Construction Practice*, 4th Edition, E & FN Spon.
- Vardanega P.J., Williamson M.G., Bolton M.D. (2012). Bored pile design in stiff clay II: mechanisms and uncertainty, *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* 165(4): 233–246.
- Whitaker, T. (1979). *The design of piled foundations*, 2nd Edition, Pergamon Press.
- Yeats, J.A., aO’Riordan, N.J. (1989). *The Design and Construction of Large Diameter Base Grouted Piles In Thanet Sand At Blackwall Yard*, London, Deep Foundations Institute.

Authors’ bios

Hilary Shields, Tony Gee and Partners (UK)

Chartered Civil Engineer CEng MICE, BA MSc DIC.

Hilary Shields is an Associate Specialist Director at Tony Gee. Her role involves design management and geotechnical analysis of retaining walls, basement design, piled and shallow foundations, including foundation re-use, earthworks, preparation of specifications for ground investigation and piling works, geotechnical reports, providing design checking, review and construction supervision. Her role includes in-house professional and technical training of early profession geotechnical engineers where she is committed to dissemination across all aspects of this field. Her experience includes seven years in research in Geotechnics at BRE, with particular emphasis on insitu testing, in particular the cone pressuremeter, and on developing semi-empirical design procedures for foundations. She undertook the MSc at Imperial College in 1995, a student of John Burland. She is currently a member of the AGS working group on Instrumentation and Monitoring and member of the DFI Committee on Foundation Reuse and is involved with the BGA early career group.

Tze Yee Yap, Tony Gee and Partners (UK)

Dr Tze Yee Yap is a Chartered Engineer with over 21 years of experience in managing and designing a wide range of geotechnical structures, such as cut-and-cover structures, shallow and pile foundations, ground improvement schemes, embankments, and cut slopes. He also specialized in the application of Finite Element Method (FEM). Tze Yee has worked across the UK, Singapore, Ireland, the United Arab Emirates, and Hong Kong.

Tze Yee has served as a reviewer for the *Proceedings of Institution Civil Engineers - Geotechnical Engineering* (in 2011, 2015, 2017 & 2021) and *Géotechnique* (2015). In additional, he was a speaker at the Institution Civil Engineers event “Infrastructure Mega Projects in the Middle East: Risks and Opportunities for UK Geotechnics” in March 2014.

Cyrus Toms, Tony Gee and Partners (UK)

Cyrus Toms is a Chartered Civil Engineer with more than 30 years’ experience in infrastructure and civil engineering design and management. He has worked in the UK, Middle East, Italy, Russia, Tunisia, Malaysia, Thailand, Philippines and Central Asia. He leads the Geotechnical Group in Tony Gee and sits on company Executive Board. Cyrus has extensive knowledge of a wide range of geotechnical fields

and his experience in geotechnical design includes deep basements; free standing earth retaining structures; large diameter bored piles, hand excavated underream piles and minipiles (micropiles); traditional shallow foundations; basement rafts. In addition, he is experienced in ground risk management, earthworks and foundation strategies, slope stability assessments and contamination risk assessment. Cyrus established and manages the a technical development programme in Tony Gee and has led a number of research projects including, Post closure assessments developing the interactions of near and far field barriers – Manchester University, Web-Based GIS for Stakeholder Involvement in Multi- Criteria Site Selection for Geological Disposal of Radioactive Waste –University College London and Near field modelling – Cardiff University.

Tarryn Chalmers, Tony Gee and Partners (UK)

Tarryn Chalmers is Associate Specialist Director at Tony Gee with experience in geotechnical design including foundation design, earthworks and cutting design, slope stability assessment, soil reinforcement, and retaining wall solutions. She is proficient in the use, and supervision of use, of analytical software from limit state analysis to finite element packages. Tarryn has worked on a wide range of infrastructure schemes including significant ports, railway projects, roads, deep excavations, and slope stabilisations for sites internationally and in the UK. Tarryn has a strong technical background in Geotechnical Engineering which she uses to deliver complex innovative solutions with constructability at the forefront. She has previously been an elected member of the National Committee of the British Geotechnical Association and supports student and graduate engineers in their professional development within Tony Gee.

Linking theory to practice: the semantic wave in a postgraduate critical state soil mechanics course

T.S. da Silva Burke

Stellenbosch University, Stellenbosch, South Africa
taliaburke@sun.ac.za

ABSTRACT: Critical state soil mechanics (CSSM) is an essential component of postgraduate geotechnical engineering education due to the integration of deformation and strength into a unified model. This paper presents the design of a postgraduate CSSM course where a combination of case studies on static liquefaction failures of tailings storage facilities (TSFs), theory lectures and practical tutorial exercises are used to move students through the semantic wave (Maton, 2013) linking concrete and abstract concepts in incremental cycles as the course progresses. A review of the key points in the semantic wave highlighted the need to allow more time for processing of complex theory and encourage thorough completion of tutorial activities. In a follow-up assignment, students replicated the slope stability round robin exercise by Reid & Fourie (2024), using field data to determine a representative in-situ state parameter and NorSand simulations to develop a state parameter–undrained yield strength ratio relationship for a limit equilibrium slope stability model. Despite detailed guidance, results varied, underscoring the need for careful CSSM model interpretation and improved instruction. While the course effectively demonstrated CSSM's relevance to TSFs, further work is needed to highlight its broader applicability in geotechnical engineering.

Keywords: critical state soil mechanics, active learning, semantic wave, static liquefaction

1 Introduction

One of the primary drivers of soil behaviour is the appreciation that soil is a particulate material. A key implication is that the interaction between individual particles and the voids between them results in the soil behaviour being a function of both the applied stresses and void ratio. Critical state soil mechanics (CSSM) is widely recognised as providing a valuable framework that unifies shear and consolidation behaviour of soils and allows prediction of soil strength and deformation as a function of initial state, loading and drainage conditions (Airey & Miao, 2016; Jaksa, 2020; das Neves, 2024; Ledesma, 2025).

There has been some debate about the appropriate level at which to introduce CSSM: Atkinson (1993), Airey & Miao (2016) and Jaksa (2020) are strong proponents of the inclusion of CSSM at the undergraduate level with the caveat that this should be a simplified CSSM concept, i.e. "the combination of shear stress, normal stress and volume into a single unifying framework" (Atkinson, 1993). Airey & Miao (2016) highlight the use of shear box test results to teach the CSSM concepts as opposed to conventional triaxial tests and related stress invariants. The reasons that this is seen as an essential component of introductory soil mechanics courses is due to the link between "consolidation, stress path and strength" (Airey and Miao, 2016) or between "load, strength and volume change" (Jaksa, 2020). Such a presentation must give appropriate emphasis to idealisations and limitations of CSSM. Wesley (2015) strongly advocated against the inclusion at an undergraduate level primarily due to excessive idealisations, the limited practical relevance to natural soils and inability of CSSM to model behaviour of both clays and sand.

With regards to postgraduate education, there is no doubt that CSSM is a valuable contribution to the full and appropriate understanding of soil mechanics, and that all specialist geotechnical engineering academics and practitioners should have an appreciation for this. This should be at least at the

conceptual level advocated above for undergraduates, but preferably more advanced with some understanding of the development of the theory, limitations and applications. Some of the challenges identified in teaching CSSM at an undergraduate level remain; one of these is the “complex, theoretical nature of CSSM” (Jaksa, 2020) and advanced mathematical skills required to fully develop the plasticity theory which may alienate and not elucidate. A second challenge is the perceived limited practical relevance due to the development of the original theory on artificial, remoulded soils (Wesley, 2015). However, as noted by Jefferies (2019), with advances in the definition of the size of the state boundary surface and the way that hardening is incorporated, “CSSM becomes applicable to all soils, all densities, and all loading paths.” Teaching of the more generic CSSM models, especially NorSand, should be advocated in addition to the traditional Cam-Clay model.

2 Development of a postgraduate course: Soil Behaviour

Stellenbosch University includes a brief introduction to CSSM as part of the undergraduate soil mechanics curriculum as per Knappett and Craig (2020). In the upgrading of one of the postgraduate courses taken by Masters' level students, Soil Behaviour, it was decided to redesign this course and to present an advanced CSSM course giving detailed focus to the development of CSSM-based constitutive models, namely Cam-Clay (Schofield & Wroth, 1968) and NorSand (Jefferies, 1993), as well as to locally relevant practical applications of the theory. CSSM was deemed to perfectly encapsulate what is meant by “soil behaviour” as it is a theory that allows the description of how a soil will behave under various loading and drainage conditions as a function of the stress and density (void ratio).

According to a survey conducted by the British Geotechnical Society in 1999, CSSM was ranked the most significant development in geotechnics over the previous 50 years (Ground Engineering, 1999; cited in Ng, 2014). Arguably one of the most significant advancements in the 25 years since is the increasing prevalence of numerical methods, especially finite element analysis, which featured fourth in the original survey results, and significant advances in computing capabilities.

Aside from the desire that those specialising in the field of geotechnical engineering have a functional grasp of CSSM, one of the primary drivers for the course focus on CSSM is the increasing prevalence of the use of numerical models in practice and a desire that those using them adequately understand how to determine appropriate input parameters for CSSM-based constitutive models and the implications of various assumptions made in the development of the models that may limit application. As noted by das Neves (2024) in differences between geotechnical engineering instruction and practice, “many users are not yet familiar with the critical states [sic] theory taught in soil mechanics courses, making it difficult [to ensure] a correct interpretation of the program results.” Many advanced numerical models are based on CSSM, and thus with research and industry incorporating numerical analyses it is important that students understand the fundamentals of the theory.

A second strong motivation for ensuring adequate knowledge and training in CSSM for graduate engineers is that in the South African geotechnical engineering community, the design of tailings storage facilities (TSFs) has become a significant and growing portion of the work undertaken. This provides an excellent opportunity for the demonstration of CSSM in practice, as this theory, and particularly the use of the state parameter, ψ , as defined by Been & Jefferies (1985), has been used extensively to predict dilative and contractive behaviour in hydraulically placed fills, and thus assess the static liquefaction potential, i.e. the potential for a brittle loss of strength in loose, saturated materials under monotonic loading, and resultant stability of these facilities (O'Brien et al., 2022).

Many advanced CSSM courses focus predominantly on the mathematical development of the models, with little practical application. This leaves students unaware of the implications and value that CSSM models can add to real engineering problems. The aim in the development of the Soil Behaviour course was to (1) balance theoretical and practical understanding (focus on conceptual understanding and not on mathematical derivations of flow rules and hardening rules, for example) and (2) encourage a more student-centered and active learning approach (McDowell, 2001).

3 Soil behaviour course overview

The course was presented in a block week (short course) format with four days of scheduled contact activities, and one optional day where the venue was available for students to work on the assignments.

The course was broadly divided into two themes: soil behaviour in the laboratory and soil behaviour in the field. Students were required to submit a post-course assignment related to each theme, due approximately 6 weeks after the course. “Soil behaviour in the laboratory” formed the bulk of the contact time (three days) and focused on understanding CSSM theory, the related constitutive models, and the appropriate specification and interpretation of laboratory tests for the required input parameters in one of the most widely used and generically applicable constitutive models, NorSand. This is typical of the content covered by advanced CSSM courses. The material for this course was based primarily on the CSSM course presented by Jefferies & Shuttle (2020) for which the course notes and presentations served as a valuable resource. Additional reference was made to Jefferies & Been (2015) and the online repository of data in the support material that accompanies this textbook. “Soil behaviour in the field” formed the final day of the contact time and focused on the use of the Cone Penetration Test with pore pressure measurement (CPTu) to determine the in-situ state parameter, ψ , of tailings using the screening methods of Plewes et al. (1992) and Robertson (2010). This component of the course was included to highlight application areas and show a clear, practical link to the use of CSSM in industry. Table 1 presents the structure of the contact time including group activities (blue), lectures (orange), and tutorials (yellow). The course included a total of four tutorials, each intended to as an opportunity to put some of the theory in practice. The basis of these tutorials is described below:

1. Calculation of the critical state parameters for critical state line (λ and Γ) from a series of five undrained triaxial tests on loose sand.
2. Calculation of the critical state parameters required to describe dilatancy (N , X and M) from a series of five drained triaxial tests on dense sand.
3. Calibration of the NorSand model to determine the hardening modulus, H , and elastic shear modulus, G_{max} , and verify the results of the final model with the laboratory data.
4. Use CPTu data to identify regions of contractive material that may be at risk of static liquefaction and determine the representative state parameter, ψ , of the liquefiable material.

Further details of the course structure and reasoning behind this is discussed in Section 4.

Table 1. Critical state soil mechanics postgraduate course schedule (as presented)

	Day 1	Day 2	Day 3	Day 4
	Soil behaviour in the laboratory	Idealisations & computations	Completed model	Soil behaviour in the field
Session 1 (1.5 hours)	Introduction	Tut 1 review (Lab. Data)	T2 continued...	CPTu testing
	Case studies	Elasticity & plasticity		In situ strength and OCR
		State boundary surface		In situ state parameter, ψ
		Cam-Clay CSSM model		
Tea & coffee break				
Session 2 (1.5 hours)	Terminology review	Drained & Undrained stress paths	Complete NorSand model	T4: CPT plotting & interpretation
	Continuum mechanics	Undrained shear strength	T3: NorSand calibration &	
	Critical state concept & CSL	Static liquefaction	verification	
	State parameter, ψ	Stress-dilatancy		
Lunch break				
Session 3 (1.5 hours)	Lab. testing to determine CSL	T2: Fitting dilatancy parameters to	T3 continued...	T4 continued...
	T1: Fitting critical state parameters to real lab. data	real lab. data		Case studies - a second look
				Conclusions

As noted previously, the module included the submission of two post-course assignments: the first required the interpretation of critical state parameters from a set of laboratory triaxial data (35%), and the second required the evaluation of the static liquefaction potential of a TSF by conducting a stability analysis (60%). The final 5% of the course mark was derived from a review of initial reflections on CSSM theory submitted prior to the course. The first assignment required the submissions of the results from tutorials 1 to 3. The second assignment was viewed as the primary integration of the course knowledge into practical application; this was based on the slope stability round robin conducted by Reid & Fourie (2024). Tutorial 4 formed the first portion of this assignment. Students were required to analyse CPTu data to characterise the extent of contractive material in the facility and to determine the representative state parameter, ψ , of this material and subsequently to use NorSand element simulations with given material input parameters to predict the peak and liquefied shear strength as a function of state parameter. These were combined into a limit equilibrium slope stability model to determine the initial

factor of safety (FOS) of the TSF, as well as the maximum height of the phreatic surface before failure would occur. Further review of Assignment 2 is given in Section 5; this was selected as it presented an interesting observation on how much variation in interpretation there was even with specific instruction and detailed resources available, highlighting the challenge in adequate understanding and consistent application of CSSM theory.

4 The semantic wave and linking theory to practice

The semantic wave is a concept developed by Maton (2013) which describes an ideal progression from abstract theories to concrete applications and back again through appropriate unpacking and repacking of meanings. A schematic representation of the wave is shown in Figure 1 where a student is presented with an abstract or complex concept that may be difficult to understand (high semantic density, low semantic gravity). This is then unpacked and brought down to a concrete example or application (low semantic density, high semantic gravity), and then repacked in integrated back into the complex range to complete the learning cycle (Curzon, 2019). This cycle can repeat throughout the learning process.

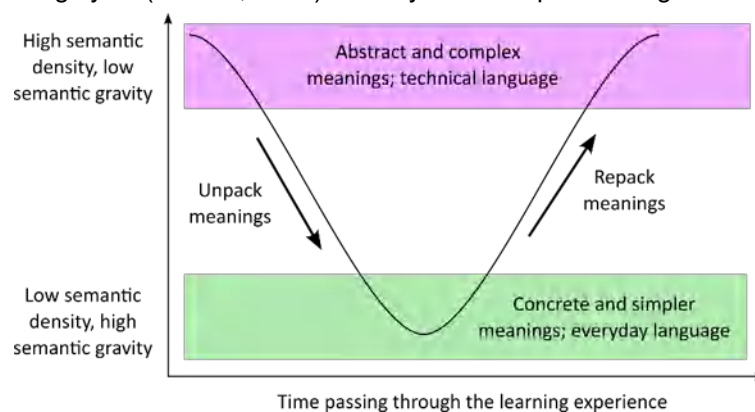


Figure 1. The semantic wave (after Maton, 2013)

In the development of the current postgraduate soil behaviour course, the semantic wave was used as a tool to help develop the linking of theory to practice with practical applications in the concrete realm, and theory in the abstract, conceptual realm. Additionally, this was used to create a balance in active and passive learning modes through the inclusion of group work (primarily case study reviews) and tutorials to stimulate active learning with a strong practical focus. Lectures were structured between these activities to introduce new complex or abstract theories (top of the wave) and/or unpack and repack their meanings between the tutorial activities (at the bottom of the wave). The idealised breakdown of the course content according to the semantic wave is shown in Figure 2. The two parts of the course (laboratory focus and field focus) created a break in the wave; the integration of these two components was completed in the second assignment. Key aspects of the semantic journey and select reflections on the implementation are unpacked in the following sections.

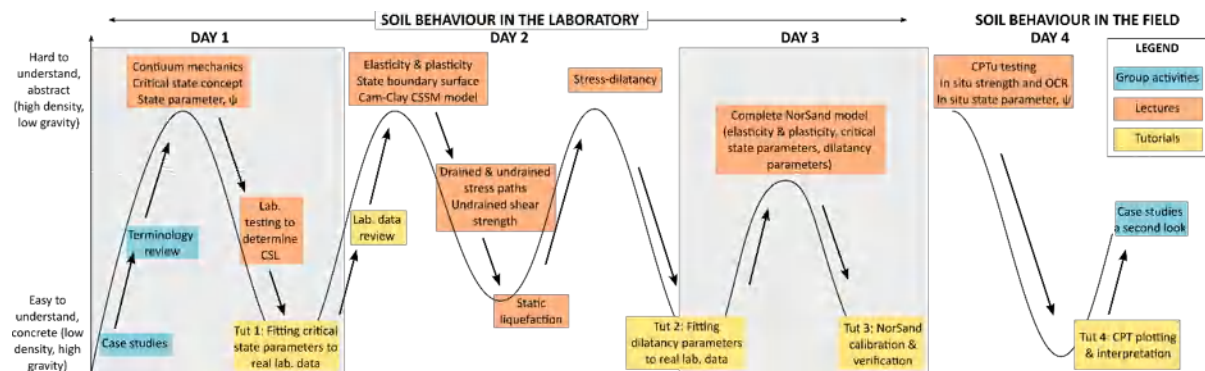


Figure 2. Breakdown of the CSSM course schedule into the semantic wave

4.1 The start – and end – of the journey: case studies

The primary mechanism to drive the link between theory and practice was the inclusion of case studies of significant static liquefaction failures of TSFs from around the world at the start and end of the course. A review of these case studies was introduced as the first activity in the schedule to anchor the importance of CSSM and how it can be used, and specifically the impact of when things go wrong. Instead of starting the learning journey in the abstract realm, it was felt that the learning would have more context and value if the applicability was clearly highlighted.

Instead of presenting the case studies as a lecture, the students were divided into groups of four or five, and each group was asked to review a separate pre-selected case study of a TSF failure to increase active participation and learning. The case studies used were the Fundão / Samarco (Brazil in 2015), Feijão / Brumadinho (Brazil in 2019), Cadia (Australia in 2018) and Merriespruit (South Africa in 1994). The students were sent information on their groups and case study the week before the course started, together with some pre-reading on CSSM (Airey and Miao, 2016; O'Brien et al., 2020; Knappett and Craig, 2020). They were asked to (1) provide general information about the TSF, (2) describe the failure and consequences, (3) give reasons for the failure as determined from the post-failure investigations, and finally (4) highlight how CSSM was used in the analysis. After a brief introduction, the course started with a 90-minute session dedicated to these case studies with the students dividing into their groups and discussing what they had read and learnt about their particular TSF. Each group had to then give a presentation to their peers related to the four questions/prompts.

The expectation when designing this activity was that students would have been more prepared before attending the course. However, although some students had spent time reviewing the material, the majority had not, and the time was consequently limited in class for each group to fully review each case study. One group divided up the questions and each person reviewed one aspect of the case study which was not the intention. Challenges included students being late and internet connectivity issues on the first day of the course, as well as low energy with students being unfamiliar with each other and perhaps unused to having to actively participate in a short course instead of listening to lectures. The major benefit of the case study review was the links that it gave me as the facilitator later in the course as I worked through the critical state concept; I could highlight points that had been mentioned in their own presentations and elaborate on their meaning now that we had more of the required technical understanding. This really engaged students in the learning process, and they could see how they were progressing through different levels of understanding. Providing specific resources that students could consult on each case study could potentially help with students being more prepared prior to the course.

The final activity in the course looked again at the case studies and students were asked to review the presentation that they put together and discuss any new insights that they had gained on these failures after what they had learnt about CSSM and the state parameter, ψ . The aim was to encourage the connection of concrete examples to abstract theory and principles that had been covered during the course and thus move the students' understanding of these case studies further up the semantic wave. This allowed students to reflect on their own learning by looking at the material that they had put together and to understand this from a new perspective. This led to a final discussion on the role CSSM plays in understanding and evaluating TSFs and static liquefaction potential. Students found it interesting to go back to the case studies again, however, not all of them work in the design of TSFs, and some of them felt that a broader range of applications of CSSM could have been highlighted in the course or at least in the final discussion of areas of application.

4.2 Moving up the first wave: terminology review

Instead of moving directly into theory from the case studies, the second activity aimed to connect everyday and technical language by giving students a list of 30 key terms used in CSSM and asking them to define them from their own understanding and check their understanding with their peers. The list included terms such as yield stress, deviatoric stress, strain hardening, dilation and elastic behaviour. This proved a valuable exercise in laying the foundation for the abstract presentation of continuum mechanics and the critical state concept which relies on a good grasp of introductory soil mechanics. This also ensured that as more technical concepts were presented through the course, there was a good understanding of the underlying terms and knowledge could be built off this base.

4.3 Wave peaks: abstract theory

The presentation of abstract concepts and new theories was delivered via traditional lectures, shown at the peak of the semantic waves in Figure 2. Where possible, short videos, interactive quizzes, and worked examples were included to consolidate learning. The first peak presented the introduction to critical state theory, including the concept of the critical state line (CSL). The second peak presented the crux of traditional CSSM culminating with the presentation of the Cam-Clay model. The third peak presented extensions to the traditional model to include further understanding of dilatancy which is necessary to ensure that the model can account for all soil behaviour, and not just remoulded clays. The fourth peak combined the elements of the prior three peaks into the complete NorSand model presentation. This concluded the laboratory and modelling section of the course. The final peak did not follow continuously from the prior material and presented a different perspective on CSSM by discussing a specific field application where CSSM is crucial. After each peak, tutorials (discussed in Section 4.4) or more practically oriented lectures and demonstrations (discussed in Section 4.5) were included to move from the abstract to the concrete realm.

4.4 Tutorials: key opportunities for concrete implementation

The four tutorials during the course were a key feature of encouraging concrete application at the bottom of the semantic wave and were structured to allow practical implementation of the theory presented in the preceding lectures. For Tutorials 1 to 3, the completed parameters from one tutorial were required for the subsequent work thus enforcing that the material is understood before progressing. These tutorials were also used as the basis for the assignment submissions required for the course with T1-T3 forming Assignment 1 (35% of course mark), and T4 used as the starting point for Assignment 2 (60% of course mark), thus adding incentive to active engagement with the material.

The tutorials formed the bulk of the contact time of the course (see Table 1) and provided ample opportunity to integrate the theory presented in the lectures into practical examples. An advantage from the teaching perspective was that for most of the tutorial work, students had to develop the required spreadsheets themselves which forced them to engage with the lecture material and review all the analysis procedures. This process facilitated good questions from the students as they checked and built their own understanding. However, completion of the data interpretations took a lot longer than expected with some students still working on earlier tutorials as the course progressed thus limiting their ability to focus on the new material in sync with the intended presentation.

From the student feedback at the end of the course, these tutorials were overwhelmingly the aspect of the course that the students found most valuable. Responses highlighted the benefit in looking at theory and then practicing the application of it incrementally, as well as having sufficient time to work through the material at a slower pace. Additionally, it was noted that by working through the tutorials, students gained the benefit of completing the course with additional tools, specifically spreadsheets, that they will be able to use in practice.

4.5 Heavy on the theory: coming down after Cam-Clay

The presentation of plasticity theory and concepts such as the state boundary surface required to understand the Cam-Clay model is technically very dense; this was presented at the start of Day 2 (second semantic wave peak, Figure 2). Although efforts were made to slow-down the pace for example by using ChatGPT to “put plasticity theory into plain language” and using interactive quizzes to periodically test knowledge, students still found this portion of the course very challenging. Student feedback at the end of the course confirmed this with a particular comment noting the difficulty in keeping on top of new content on the second day. There was no tutorial directly after this peak, in this case, the ‘unpacking’ of this theory was done by reviewing the stress paths that would be followed in various triaxial tests with various drainage conditions (drained and undrained) and from various initial conditions (overconsolidated and normally consolidated). This included drawing the stress paths by hand and calculating undrained shear strength at failure in worked examples. Whilst still abstract, the students should be familiar with the triaxial tests and some test results from these, so presenting a theoretical model that described why the paths take the shape they do is a helpful stepping stone.

Two tools proved especially valuable in these demonstrations. The first was digital: a MATLAB-based virtual interactive 3D model based off those developed and published by Medicus (2020) and the accompanying animated stress paths for drained and undrained triaxial tests for normally consolidated,

lightly overconsolidated and highly overconsolidated material. The 3D model allowed one to 'look inside' the state boundary surface and view it from all angles and see how it grows and shrinks under different conditions. The animated stress paths showed the 2D representations of this model.

The second tool which proved valuable was the use of physical 3D printed models of the Cam-Clay state boundary surface to assist in the three-dimensional visualisation of the model and specifically predicting the stress path and failure point of a triaxial soil test depending on initial state, loading and drainage conditions. Curzon (2019) notes in particular how illustration of the explanation with physical props is helpful in descending the semantic wave and bring abstract concepts towards the concrete realm. Having the 3D models was immensely helpful in, for example, physically drawing the stress-path that a test would take in 3D and showing how that stress path moves along the state boundary surface in three dimensions compared to the 2D visualisations that are commonly shown. One limitation was the small size of the models (approximately 150 x 150 x 100 mm), and in future I would print as big a model as possible (or even better, give each student their own model to explore).

4.6 Post course reflections on semantic wave

Following the presentation of the course, several items were noted where the progression through the semantic wave did not follow the intended course and where additional support could be inserted to achieve better flow. The first wave worked well, and starting in the concrete realm with the case studies provided an anchor to reality throughout the course in both presentation of abstract theory and analysis of data in the tutorials. The first challenge that was experienced related to the tutorials taking longer than expected: not all the students had completed the derivation of the CSL parameters (Tutorial 1) before moving on to the 'heavy' theory and mathematics of the full CSSM model on Day 2. This had a knock-on effect on Tutorials 2 and 3, and was especially evident in the latter where many students did not properly understand how to conduct element simulations in the provided spreadsheet. A suggestion to aid improvement is that instead of Tutorials 1 to 3 forming a single assignment submitted after the course, these should be submitted during the course to encourage timeous completion of the activities and thus ensure that further understanding is not compromised by being behind. A peer review of these submissions could be incorporated to strengthen peer-to-peer learning and provide more feedback.

The second challenge was that the 'unpacking' of the material after the second peak (Section 4.5) remained for many of the students at the complex, technical level, despite efforts made to contextualize this (e.g. physical and virtual models, worked examples, presentation on static liquefaction to give the theoretical background to the case studies that had already been reviewed). The teaching of theory went far quicker than anticipated which was beneficial to allow more time for the tutorials, but this could also be used to add a more concrete demonstration of the CSSM theory, for example including simulations of triaxial tests or more activities to draw more stress paths themselves to help process the theory.

5 Slope stability round robin comparison – Assignment 2

The second assignment aimed to consolidate the laboratory and field applications of CSSM by showing how critical state parameters derived from triaxial data and CPTu data can be combined to complete stability analyses of a TSF. The assignment was based on the Reid & Fourie (2024) slope stability round robin exercise which was originally conducted to compare how reliably and consistently engineers analyse the stability of TSFs. In this exercise, participants were provided with CPTu data and NorSand critical state parameters for two facilities and required to predict the height of the phreatic surface at which failure of the hypothetical facilities occurred. 28 responses were received; the majority of the submissions used the Plewes et al. (1992) and Robertson (2010) screening methods to estimate the state parameter, ψ . 18 submissions used limit equilibrium methods to predict the failure with six of these using NorSand element simulations to determine the yield strength ratio (YSR) as a function of state parameter.

For the assignment, students were required to replicate this exercise and additionally calculate the initial FOS of each facility. It was specified that NorSand element simulations were to be used to develop the ψ -YSR relationship and to specify the YSR used in the stability limit equilibrium model based on the representative state parameter, ψ , below the phreatic surface. The Reid & Fourie (2024) publication with the results and analysis of the round robin exercise was made available to students together with all the

source data. The CPTu analysis required for the assignment formed Tutorial 4 that was covered during the course schedule.

The submitted results showed wide variations in understanding and interpretation of CSSM. Limitations in understanding were noted in the following areas (1) appropriate use of screening methods to select the state parameter, (2) accuracy of NorSand element simulations and (3) appropriate specification of limit equilibrium methods. Elaboration of each of these is provided in the following paragraphs. This highlights opportunities for improvement in ensuring full and appropriate understanding and application of CSSM.

5.1 Selection of state parameter

The two CPTu datasets of Reid & Fourie (2024) had drained penetration conditions for the first case (Scenario A) and undrained for the second (Scenario B). In the review of the participant submissions, they noted that several submissions applied the Robertson (2010) screening method to estimate ψ for Scenario B, “despite this scenario featuring undrained penetration conditions likely outside the range of applicability of the method.” In the review of the student assignment submissions, many students used both screening methods to estimate ψ despite it not being applicable to Scenario B, and despite the available information given in class and in the Reid & Fourie (2024) paper noting such. A related error in understanding was the confusion of drained and undrained *penetration conditions* with drained and undrained *analysis*. Some students noted that the Robertson method was not applicable because an undrained stability analysis was required, which is not correct. This shows that the concept of drained and undrained behaviour remains a challenge for some students to grasp, even at postgraduate level.

A wide discrepancy was noted in the way that a representative state parameter, ψ , was chosen. Jefferies & Been (2015) recommend the use of an 80th percentile value to provide a conservative estimate given the uncertainty of the correlations. In contrast, the Robertson (2010) method suggests using the mean value for design purposes. In the Reid & Fourie (2024) submissions, participants tended to use either the 50th or the 80th percentile. The student submissions varied more widely with some students using the 20th or 30th percentile, with the majority using the 50th percentile or the mean. This difference had the widest impact on the stability results.

5.2 NorSand element simulations

The NorSand element simulations required to determine the ψ –YSR relationship had been demonstrated in the tutorials as part of the calibration and verification of the complete NorSand model (Tutorial 3). However, many students required additional support during the assignment period in how to extract the yield strength at each specified state parameter as this understanding was not clear to them. This was partly because of the prior issue where students used the time to complete the earlier tutorial work and did not fully complete Tutorial 3 in the allotted time. In reviewing the accuracy of NorSand element simulation results, it was found that the majority of the students used a pair of ψ –YSR values that corresponded to the expected results. Some variance existed due to differences in the coefficient of lateral stress and the confining pressure used in the simulations.

5.3 Limit equilibrium modelling

When modelling the undrained shear strength of a soil using the YSR in a limit equilibrium slope stability model, the most appropriate soil model to use is the SHANSEP (Stress History and Normalized Soil Engineering Properties) model. One of the deficiencies identified in the submitted assignments was that students used the default material parameters without fully understanding the model or appropriately adapting it for the analysis. The model had been presented during the course, but no opportunities to put it into practice were offered as the aim of the course was the understanding of CSSM and not slope stability analysis. A related error that occurred was that some students used a Mohr-Coulomb soil model for the undrained analysis, even after going through the procedure to calculate the YSR. Others used undrained material parameters above the water table and did not appreciate that drained strength parameters should be used here. Other errors in the stability modelling included incorrect values for drained friction angle used above the phreatic surface and variation in the unit weight of the soil, despite these values being specified in the input and/or supplementary material.

The results of the FOS calculation showed an average FOS of 1.47 for Scenario A with a variance of 26% (min:0.82, max: 1.84), and an average of 1.31 for Scenario B with a variance of 32% (min:0.87, max: 1.9). Consequently, there was a wide range of answers in the level of the phreatic surface at failure with some students predicting that the facilities would fail in the initial condition ($H = 25$ m), and other predicting a rise to 95 to 103 m for failure for Scenario A and B respectively.

A common reasoning to the variability in results from round robin design exercises is the contribution of the time that participants spend in completing the exercise, and the expectation that this is less than the effort that would be applied in a design situation resulting in less accurate results. Similarly, differences in skill, experience and training would all contribute to the variability. The results from the students showed a surprising variability in all respects: from assumptions of input parameters to final results (FOS and phreatic surface height at failure). This is considered 'surprising' as the students all received training in the appropriate methods and assumptions, specifically in the analysis of the CPTu data. Additionally, due to the assignment comprising 60% of the course mark, there was incentive to complete the exercise thoroughly. Students also had access to the Reid & Fourie (2024) paper to evaluate the submissions made by other participants in the same design exercise, but very few evaluated their results in the context of those in the paper where similar procedures had been followed. This highlights the need for careful CSSM model interpretation and improved instruction, specifically in relation to how these assumptions are translated in limit equilibrium models.

5.4 Assignment reflections

After the completion of the course, the aim was that the students would be able to integrate the two components of knowledge represented in the two separate semantic waves in Figure 2 (soil behaviour in the laboratory and soil behaviour in the field) themselves through the completion of the assignment, especially with the Reid & Fourie (2024) paper to guide them. In reality, this was still quite a jump for most students: the first part of the course concluded with the presentation of a complete CSSM model, and the second part of the course showed how to determine where liquefiable material is present. There was no presentation of how these can be integrated, for example in stability modelling. Adding this element would allow a better understanding of the full cycle of implementation of CSSM. Furthermore, additional examples of how CSSM can be used, for example in advanced numerical modelling such as finite element modelling of deformations would be beneficial to show integration of the two components of soil behaviour.

6 Concluding remarks

The development of the CSSM postgraduate course provided an interesting opportunity to explore why CSSM has proven to be such a valuable theory and framework and to identify the ways that CSSM is used in the local geotechnical community. A basic grasp of CSSM is considered essential for specialist geotechnical engineers because of the way that this model captures the particulate nature of soil and the resultant dependency of the behaviour on both density (void ratio) and applied stresses. Even for engineers who do not conduct advanced numerical modelling or analysis of TSFs that incorporate CSSM, this unified framework of shear and consolidation behaviour is a helpful tool to help explain why soil behaves the way it does under various loading and drainage conditions.

The concept of the semantic wave provided a useful framework to link concrete examples and abstract concepts throughout the course, and to ensure an incremental progression through waves between the two bounds. Case studies and tutorials were used to encourage active learning and to help contextualize the abstract theory presented in lectures. Physical and virtual models helped with moving from the complex to the simpler realm. Whilst the expectation may have been that some of the presentations were moving down the semantic wave and unpacking meanings, these may have remained at a level that the students found hard to understand for extended periods before they had the chance to put their learning into practice. Additional reviews of the expected tutorial activities would have been beneficial to transition back into the technical lectures after students had spent time analysing data.

The replication of the Reid & Fourie (2024) slope stability round robin showed surprising variance in analysis methods used and final stability results, despite detailed guidance given and the analysis of the CPTu data during one of the allocated tutorial periods. This variance was primarily in the way that a representative state parameter was selected, although several errors in the limit equilibrium modelling

were also noted highlighting the need for careful CSSM model interpretation and improved instruction. While the course effectively demonstrated CSSM's relevance to TSFs, further work is needed to highlight its broader applicability in geotechnical engineering.

Acknowledgements

Thanks to Prof. Karin Wolff, Associate Professor of Teaching & Learning in the Dean's Division, Engineering Faculty, Stellenbosch University for her suggestion to use the semantic wave as a tool to progress through various abstract and concrete concepts through the course.

References

- Atkinson, J. (1993). *An Introduction to the Mechanics of Soils and Foundations Through Critical State Soil Mechanics*, first ed. McGraw Hill, London, UK.
- Airey, D., Miao, G. (2016). Why Critical State Soil Mechanics Should be Taught to All Civil Engineers. *Proceedings of ISSMGE International Conference Shaping the Future of Geotechnical Education, SFGE 2016*, Belo Horizonte, Brazil, Oct. 20-21.
- Been, K., Jefferies, M.G. (1985). A state parameter for sands. *Géotechnique*, 35 (2), pp. 99–112
- Curzon, P. (2019). Tip 9: Follow Semantic Waves— Learning To Learn (To Program). helloworld.cc/semantic5
- das Neves, E. M. (2024). Teaching modern soil mechanics. *Soils and Rocks*, 47(2), e2024006823.
- Jaksa, M.B. (2020). Reflections on some contemporary aspects of geotechnical engineering education—from critical state to virtual immersion. *Proceedings of ISSMGE the Online International Conference on Geotechnical Engineering Education 2020 (GEE2020)* (pp. 1-16), streamed from Athens, Greece, June 23-25.
- Jefferies, M.G. (1993). Nor-Sand: a simple critical state model for sand. *Géotechnique*, 43(1), pp. 91 – 103.
- Jefferies, M.G. (2019). Utility of Critical State Soil Mechanics. *Proceedings of 13th Australia New Zealand Conf. on Geomechanics*, Acosta-Martinez, H. & Lehane, B. (Eds.), Perth, Australia, pp. 51-56.
- Jefferies, M., Been, K. (2015). *Soil liquefaction: a critical state approach*. CRC Press.
- Jefferies, M., Shuttle, D. (2020). Vancouver Geotechnical Society Workshop. *Critical State Soil Mechanics: Notes*. <http://v-g-s.ca/2020-cssm-short-course>
- Knappett, J., Craig, R.F. (2020). *Craig's Soil Mechanics*, 9th Ed. London: Spon Press.
- Ledesma, A. (2025). Discussion of "Teaching Modern Soil Mechanics". *Soils and Rocks*, 48(1), e2025007424.
- Maton, K. (2013). Making semantic waves: a key to cumulative knowledge-building. *Linguistics and Education*, 24, pp. 8-22.
- McDowell, G. R. (2001). A student-centred learning approach to teaching soil mechanics. *International Journal of Engineering Education*, 17(3), pp. 255-260.
- Medicus, G. (2020). Animating Soil Models. <https://soilmodels.com/soilanim/>
- Ng, C.W.W. (2014). The state-of-the-art centrifuge modelling of geotechnical problems at HKUST. *Journal of Zhejiang university SCIENCE A*, 15(1), pp. 1–21.
- O'Brien, K., O'Brien, T., Robinson, B. (2022). The "critical state" of our tailings dams. *Civil Engineering*, 30(3), pp. 10 – 16.
- Plewes, H.D., Davies, M.P., Jefferies, M.G. (1992). CPT based screening procedure for evaluation liquefaction susceptibility. *45th Canadian Geotechnical Conference*, pp. 41–49.
- Reid, D., Fourie, A. (2024). Development and outcomes of a tailings slope stability comparative design exercise. *Canadian Geotechnical Journal*, 61(8), pp.1683-1704.
- Robertson, P.K. (2010). Estimating in-situ state parameter and friction angle in sandy soils from the CPT. *2nd International Symposium on Cone Penetration Testing*, Huntington Beach, CA, USA.
- Schofield, A., Wroth, P. (1968). *Critical State Soil Mechanics*, McGraw Hill, London, UK.
- Wesley, L. (2015). (What) To teach or not to teach - from theory to practice. *Geotechnical Research*, 2(4), pp. 139-147.

Author's bio

Talia S. da Silva Burke, Stellenbosch University (South Africa)

Dr Talia da Silva Burke is a senior lecturer in Geotechnical Engineering the Department of Civil Engineering at Stellenbosch University. She completed her PhD at the University of Cambridge where she conducted centrifuge modelling to investigate how geosynthetic-reinforced soils respond to the formation of underground voids (e.g. sinkholes). Talia's research interests are related to arching in granular soils, sinkhole deformation mechanisms, geosynthetics and fibre-optic monitoring. She is registered as a professional engineer under the Engineering Council of South Africa and is passionate about teaching and training future engineers to serve society.

Teaching soil mechanics in a changing world

A.M. Tang¹, J.M. Pereira¹, F. Cuira² & M. Vandamme¹

¹*Ecole nationale des ponts et chaussées – Institut Polytechnique de Paris, Marne-la-Vallée, France*
anh-minh.tang@enpc.fr, jean-michel.pereira@enpc.fr, matthieu.vandamme@enpc.fr

²*Setec, Paris, France*
fahd.cuira@setec.com

ABSTRACT: Geotechnical engineers face a changing world in which the need for new approaches in the wake of climate change presents both a challenge and an opportunity for constructing and maintaining existing infrastructures. It is thus crucial to adapt teaching soil mechanics, of which the basic concepts were established in the 20th century, to the new context. At the "École nationale des ponts et chaussées", France, the Department of Civil Engineering and Construction's students can consolidate the scientific bases of various fields while learning to be flexible and adapt to any new situation. In addition to the essential and basic concepts of standard Soil Mechanics taught in traditional lectures and hands-on sessions, two projects are introduced. The first is a literature review, allowing the students a quick global view of the current problems in Geotechnical Engineering. The second is a modelling project where the students use constitutive laws to simulate some standard laboratory tests. Besides, the contents of the Soil Mechanics class and other related classes, essentially the Geotechnical Designs class, are closely coordinated. This approach would allow graduate students to quickly learn new technologies and tools and solve problems that cannot be dealt with by standard soil mechanics knowledge.

Keywords: Soil mechanics, future challenges, adaptation

1 Introduction

Climate changes are significantly impacting all human activities. For geotechnical engineering, the need for new approaches in the wake of climate change presents both a challenge and an opportunity for constructing and maintaining existing infrastructures. For instance, climate change creates a dynamic environment where a steady state cannot be assumed when designing new infrastructure and determining operating and maintenance strategies. Figure 1 shows an example of complex patterns and interactions driven by atmosphere-vegetation-soil interactions, which play an essential role in the stability of engineered slopes (Tang et al., 2018). Besides, developing new digital technologies has provided new tools and significantly changed engineers' daily work. These tools include software for numerical simulations, devices for site investigation such as LiDAR (Light Detection and Ranging) and drone technologies, approaches to big data analyses (such as Machine Learning), etc. It is thus crucial to adapt teaching soil mechanics, of which the basic concepts were established in the 20th century, to the new context. That would help the new geotechnical engineer generation prepare for future challenges.

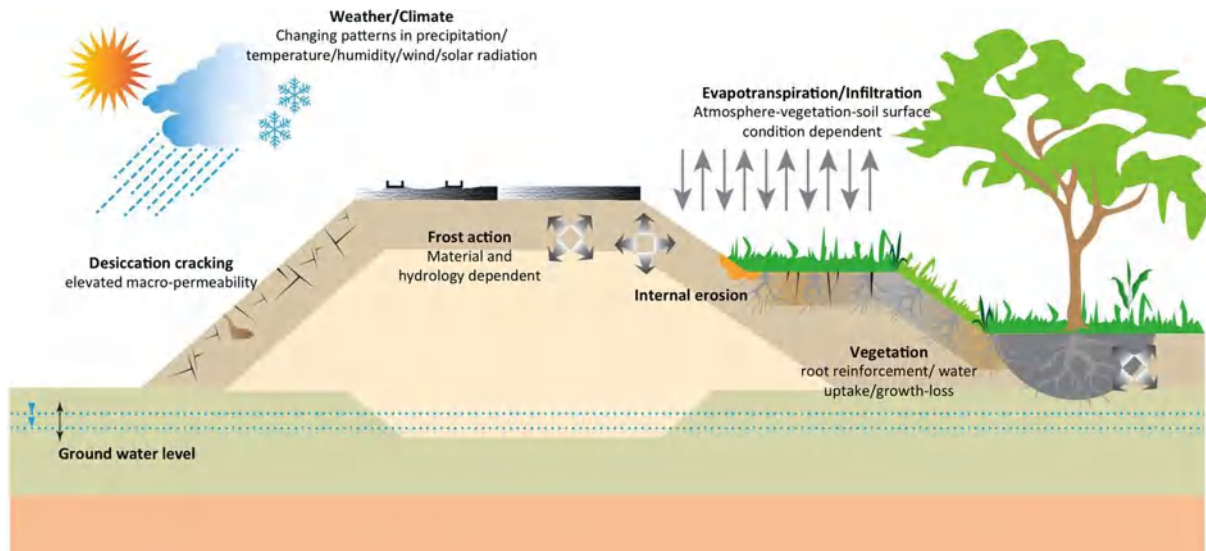


Figure 1. Example of climate-driven processes related to geotechnical infrastructures (Tang et al., 2018)

Atkinson (2008) considered that geotechnical engineers must be able to construct a geotechnical model, use total and effective stress analyses correctly, carry out basic analyses, determine design parameters, and complete safe and economical designs. They acquire these skills through education, training and experience. Burland (2008) used the concept of “The Geotechnical Triangle”, Figure 2, to represent the four distinct but interlinked aspects in geotechnical engineering: (1) The ground profile, including groundwater conditions; (2) The measured or observed behaviour of the ground; (3) Analytical prediction using appropriate models; (4) and empirical procedures, judgment based on precedent. He noted that this concept is helpful during a lecture in the soil mechanics course to point out which aspect of the Triangle is being discussed and how it relates to the other elements.

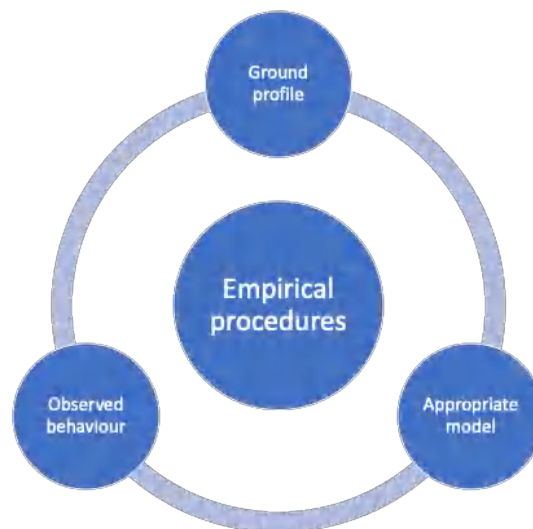


Figure 2. The Geotechnical Triangle (Modified from Burland, 2008)

In the last decade, there have been discussions about what topics should be kept and which should be discarded in teaching soil mechanics. One of the issues raised was whether critical state soil mechanics (CSSM) should have a place in an undergraduate education. Airey & Miao (2016) argued that CSSM, or at least the basics of it, are essential to understanding soil mechanics and should be a non-negotiable part of introductory soil mechanics. They considered that CSSM is also the starting point for any course on soil behaviour, and it provides a framework that enables practitioners to understand soil mechanics and the link between consolidation, stress path and strength. Maranha das Neves (2024) also considered that the vital role of the critical state theory in modern soil mechanics is undeniable. Still, the number of soil mechanics courses that do not cover this subject is progressively decreasing. Ledesma (2025) agreed with Maranha das Neves (2024) and added three general reasons to teach the basic

concept of CSSM at the undergraduate level as follows: (1) CSSM can well explain the plasticity in soil mechanics; (2) CSSM can help to understand the role of loading and unloading processes and the stiffness associated to each path; (3) CSSM provides a single set of parameters for the soils without differentiating normally-consolidated and over-consolidated clays. Wesley (2015) considered teaching material with little or no relevance to practical engineering, such as CSSM, to be of no use in undergraduate courses.

Beyond CSSM, Santamarina (2015) discussed the question “What to teach or not teach” in soil mechanics in the context when geotechnical engineering students will face today’s prevailing difficulties as well as new and demanding geotechnical challenges such as those associated with energy and the environment. Santamarina (2015) suggested that geotechnical engineering teachers must review their educational programs: (a) to reconsider the role of empiricism; (b) to prune incorrect concepts and biases (e.g., terms with multiple semantics such as “clay”, enduring misnomers such as “cohesive soil”, incorrect explanations such as sequential primary and secondary consolidations, superseded graphical approaches that have become detached from their physical-mathematical underpinning, unsound tricks such as ‘buoyant unit weight’, fragile correlations with local validity, and education based on extremes (dry–saturated, clay–sand, drained–undrained)); (c) to promote a careful understanding of fundamentals (e.g., the particulate nature of soils and fractured rocks, formation history, the essential relevance of effective stress, thermo-hydro-chemo-mechanical coupled processes, repetitive loads and ubiquitous localisations).

In terms of teaching approach, McDowell (2001) undertook a study to establish the effectiveness of a student-centred learning approach to teaching students’ applications of CSSM taught more transmissively in lectures and to determine whether such an approach significantly enhances the learning of the theory. A teach-yourself coursework handout was designed to facilitate learning of applications of a problematic theoretical subject. The study suggested that students benefited from the new ‘teach-yourself’ approach and have an enhanced ability to apply fundamental principles to high-level unseen problem-solving. Macedo & Pinho-Lopes (2024) presented a pedagogical practice combining hands-on and team-based learning to promote deep learning of basic concepts in soil mechanics: phase relationship and total and effective stresses in soils. The results suggested that using technology while adopting hands-on strategies (with simple physical models and illustrations) and promoting critical thinking is an excellent way of fostering engagement and deep learning in soil mechanics. Atkinson (2008) distinguished between education and training when discussing how geotechnical engineers acquire competence. Education deals with basic principles; it includes the behaviour of ideal soils and rocks and ideal foundations and slopes. Training deals with how to apply this education in practice; it includes the use of standards and codes of practice and the practice of getting things done.

This paper describes how “soil mechanics” is taught at the “Ecole nationale des ponts et chaussées” (ENPC) for undergraduate students of the Department of Civil Engineering and Construction in the context of a changing world.

2 Background of students attending the soil mechanics course

ENPC is a higher education institution that trains engineers to a high scientific, technical and general competency level. Apart from civil engineering and spatial planning, historically the source of prestige, ENPC develops high-quality programs and research associated with the energy transition. It is one of the most prestigious French Engineering Schools, “Grandes écoles”, which are similar to universities but typically offer a more specialised three-year course of study in business, public administration, or engineering. In France, students are admitted to the “Grandes écoles” based on their scores on a competitive exam. Before taking this exam, students must have obtained a baccalauréat and often have taken a two-year preparatory course (“classes préparatoires” or “prépas”). Students graduate from a “Grande école” with an engineering degree, which is the same level as a master’s degree (master).

ENPC’s engineering program takes three years: a first year on the core curriculum and two years of specialisation (Master program). The first year is primarily a year of transition between basic scientific education and new disciplinary fields, but also to new ways of working, with international mobility possible. It aims to (1) consolidate scientific foundations in the ENPC’s key disciplines, principally mathematics, computer science, and mechanics; (2) discover new disciplines, particularly economics and social sciences. Students will learn to develop a vision that is simultaneously scientific, technical,

economic, human, innovative, multicultural, and sustainable. In the second year, students choose one of the six curricula provided by the ENPC's specialty departments (Master program): Civil Engineering and Construction; City, Environment, Transportation; Mechanical Engineering and Materials Science; Industrial Engineering; Economics, Management, Finance; Applied Mathematics and Computer Science. In the second semester of the third year, students complete an End of Course Project on a scientific or technical problem, applying the skills acquired during their studies to a project undertaken in a company or a laboratory.

At the Department of Civil Engineering and Construction, students can consolidate the scientific bases of various fields while learning to be flexible and adapt to any new situation. An emphasis on mathematics helps develop their capacity for abstraction, contributing to their adaptability. The curriculum of the department includes (1) theoretical foundations of mechanics and dynamics applied to structures, soils, and fluids; (2) a choice of further work on geotechnics, marine structures, the structures or energy properties of buildings, combining theoretical courses and experiment; (3) two long projects (building, bridge, port, road, or dam) involving technical experiment and the learning of design methods; (4) instruction on a wide range of more specific topics, covering all aspects of civil engineering and construction, as chosen by the student; (5) seminars.

3 Soil mechanics course

At ENPC, the soil mechanics course is mandatory for all students of the Department of Civil Engineering and Construction (ca. 90 per year) in the first semester of the second year (S3). The students are divided into three sub-groups (of ca. 30), each led by one teacher. Except for a few lectures addressed to the whole group, most activities are organised by sub-group. In addition to the essential and basic concepts of standard soil mechanics taught in traditional lectures and hands-on sessions, two projects are introduced. The first is a literature review, allowing the students a quick global view of the current problems in Geotechnical Engineering. The second is a modelling project where the students use constitutive laws to simulate some standard laboratory tests.

3.1 Lectures and hands-on sessions

A typical class includes a traditional lecture (1h) followed by a hands-on session (1h30). In the lecture, the teacher provides the basic knowledge and concepts; in the hands-on session, the students learn to solve problems related to the theoretical part. The following points are addressed in this course (the time allocation for each topic is also shown):

- Introduction to soil mechanics (2h30): soil description, phase relationships, soil classification;
- Soil mechanics (2h30): total and effective stress in soil, application of continuum mechanics, stress state in the ground;
- Ground water flow (2h30): Darcy law, hydraulic conductivity, hydraulic head, etc.;
- Introduction to poromechanics (2h30): poroelasticity, rock mechanics;
- Consolidation and settlement in saturated fine-grained soils (2h30): oedometer tests, theory of consolidation, calculation of ground settlement;
- Soil behaviour under deviatoric stress (5h00): stress-strain relationship, shear strength, Mohr-Coulomb criterion;
- Applications in geotechnical engineering (2h30): stress change in the ground induced by a construction on the ground surface, stability of a retaining wall;
- Constitutive models (5h00): Linear elastic - perfectly plastic model, modified Cam Clay model.

It should be noted that the "standard" soil mechanics concepts are included in this course. The teachers focus on the physical meanings and approaches of each idea. The Geotechnical Triangle (Burland, 2008) avoids confusion between observations and models, real soils and idealised materials. Introducing poromechanics helps to extend teaching examples to a wide range of fluids, pressure, effective stress and temperature conditions that upcoming geotechnical problems will impose (Santamarina, 2015).

3.2 Literature review project

The project aims to conduct a literature review on a specific geotechnical engineering topic and present a synthesis. The suggested topics include soil improvement technologies (artificial ground freezing, jet grouting, cement and lime treatments, soil compaction, geosynthetics, rigid inclusions, etc.), geotechnical structures (shallow foundations, deep foundations, offshore foundations, geothermal structures, reinforced earth retaining walls, tunnels, deep excavations, waste disposals, railway platforms, slopes, mining dams, earth dams, retaining walls, etc.), geotechnical phenomena (erosion in embankments, soil liquefaction, clay shrink/swell, soil atmosphere interaction, collapsible soils, etc.), soil characteristics (e.g., hydraulic conductivity), soil characterisation (e.g., field tests), case studies (the Leaning Tower of Pisa, the Teton Dam, the Malpasset Dam, the CIGEO project at Bure, the ground subsidence in the City of Mexico, the La Clapière landslide, the Nicoll Highway collapse, etc.), geotechnical techniques (ground water lowering) or other topics (artificial intelligence and big data, extraterrestrial infrastructure construction, etc.).

Groups of two students conduct the project. After researching the chosen topic, the group presents the project in 5 minutes by synthesising the essential aspects, including the theoretical background, the experimental techniques, the practice, the standards, etc. The presentation can follow the usual plan: context, general principles, applications, geotechnical issues, advantages and disadvantages, open discussions, etc. The other students in the class and the teacher evaluate the presentation.

The students choose their topic from the beginning of the course and present their work after five classes. The feedback shows that this bibliographical project provides a quick view of how soil mechanics (and geotechnical engineering in a more general way) can help understand various aspects that engineering can deal with. The suggested topics are numerous and go beyond the “standard” geotechnical engineering activities.

3.3 Constitutive modelling project

This project aims to implement constitutive models presented in the course (Linear elastic - perfectly plastic model, modified Cam Clay model). A set of parameters is provided. The students are free to choose the tools for coding (Python, Excel, Matlab, etc.). The most common laboratory tests in soil mechanics are simulated: oedometer, isotropic, and triaxial compression under drained or undrained conditions. The report should explain the details of the numerical implementation (e.g., incremental loading, plasticity criterion, etc.) and provide the results in standard graphical plots. Groups of two students conduct the project, and the evaluation is based on the final report.

4 Related courses

Besides, the contents of the soil mechanics class and other related classes, essentially the Geotechnical Designs class, are closely coordinated. In the last year of studies, the students follow a class on Life Cycle Analysis (LCA), which gives them the tools to evaluate the impact of their projects, not only in terms of contribution to climate change but also to the other categories of the environmental impacts (ecotoxicity, land occupation etc.). In this final year, an infrastructure design project, intertwined with the application part of this LCA class, complements their studies. This approach would allow graduate students to join various companies working on geotechnical engineering-related projects in multiple countries. They could also quickly learn new technologies and tools and solve problems that cannot be solved with standard soil mechanics knowledge.

4.1 Geotechnical design

This course can be considered as the “training” part following the “education” part, which is the soil mechanics course (following the definition by Atkinson, 2008). Attending this course, the students will be able to analyse the geological and hydrological context of the ground to design a geotechnical structure. They can master the basics of designing the main geotechnical structures (such as foundations and retaining structures) by considering the mechanisms of soil-structure interaction and environmental constraints. The course teaches future engineers about the challenges in geotechnical design, the different calculation methods (limit equilibrium, limit analysis, finite element, etc.), and the design standards.

A typical class includes a traditional lecture (30 minutes) followed by a hands-on session (2 hours). In the lecture, the teacher provides the design principles of the geostructures, while in the hands-on session, the students will learn to design real structures. The three principal topics are covered: (1) geology, hydrogeology and the environment; (2) design of shallow and deep foundations – stability and displacement; (3) design of retaining structures – soil/structure interactions.

Throughout the course, the students work in groups of three or four, each group on one case study.

4.2 Life Cycle Analysis (LCA)

In semester 5, all students from the Department of Civil Engineering and Construction follow a class on Life Cycle Analysis (LCA). This class aims to provide them with the elements they need to master the basics of this method so that, under the guidance of an experienced project manager, they can carry out an LCA study or analyze an existing study. More than on norms and regulations, the class focuses on the methodology of LCA, its underlying hypotheses, and the databases used as inputs to invite the students to adopt a critical point of view. The first half of this class is devoted to the theory of the LCA, while the second half is devoted to an application.

In this same semester, all students undertake a design project on one of the following topics: bridge, road, dam, bioclimatic building, or marine energy. This project, on which they work about 1.5 days per week, focuses on technical design and includes classes by experts from the industry (including from the geotechnical industry when relevant), which the students readily apply to their design project. They devote the application part of the LCA class to the object of their design project. By doing so, the students can address not only the technical dimension of their project but also its environmental dimension. This interaction between technical design and LCA makes them realize the environmental implications of their technical choices and gives them the opportunity to observe an object with complementary points of view (i.e., technical and environmental), which invites them to adopt a systemic point of view.

4.3 Others

In the Department of Civil Engineering and Construction, the soil mechanics course can be considered the entry point for geotechnical engineering. The course is compulsory for all Department students in Semester 3 (Figure 3). From Semester 4, students can choose various optional courses related to geotechnical engineering.

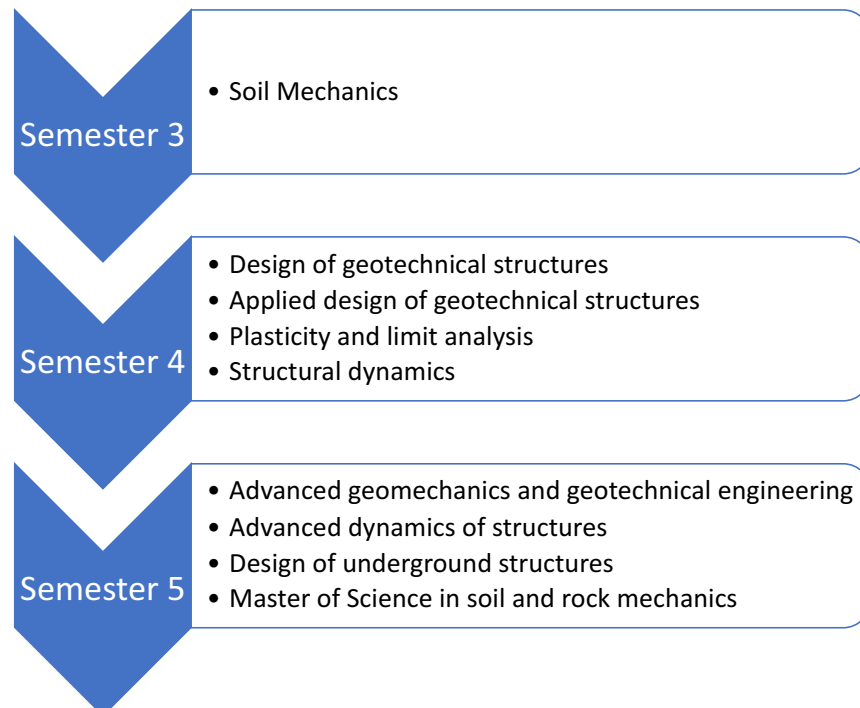


Figure 3. Courses related to Geotechnical Engineering

5 Discussion

The soil mechanics course at ENPC was designed to provide future civil engineers with the most important basic aspects of geotechnical engineering while encouraging agility to face new challenges in the changing world. More than half of the classes focus on the essential concepts in soil mechanics such as phase relations, Terzaghi effective stress, Darcy law, consolidation, soil settlement, oedometer test, shear strength, triaxial compression tests, Mohr-Coulomb criterion, etc. As the students already have an excellent background in mathematics, physics and mechanics, emphasis was placed on the Geotechnical Triangle (Burland, 2008) to link the practice and the theory. The other part of the course prepare future engineers for the changing world. That includes the introduction of poromechanics, which extends the stress range and types of pore fluids (recommended by Santamarina, 2015). In addition, the bibliographical projects provide a broader view of how soil mechanics can be used in various contexts that future engineers may face. Finally, the constitutive modelling projects help to better interpret and understand the mechanical behaviour of soil via the CSSM as suggested by Airey & Miao (2016) and Maranha das Neves (2024). In addition, by implementing the models to simulate several tests, the students can master the models that engineers use more frequently in finite element software.

The link between the soil mechanics course and the other related courses is also essential. While the soil mechanics course is mandatory for all Department of Civil Engineering and Construction students, the other Geotechnical Engineering courses are optional. That means some students may become civil engineers while only taking the soil mechanics course related to geotechnical engineering. For this reason, some applications (stress in the ground, retaining walls, etc.) are introduced in the course. For other students who attend the geotechnical design course in Semester 4, the soil mechanics course provides a good “education” base to continue the “training” course (following the concept of Atkinson, 2008).

The feedback from the students who have attended the soil mechanics course is generally favourable. They appreciate the good balance between the lecture and the hands-on sessions. Most are motivated when working on the proposed projects (literature review and constitutive modelling) because they can learn actively. In addition, most of the students at ENPC spend a gap year (between the second and the final year) to work in industry. The End of Course Project is also usually undertaken in a company during the last semester of the third year. In these industrial contexts, the knowledge and skills acquired from the soil mechanics course are usually mentioned when the students work on geotechnical projects with a high level of complexity.

Most course activities are organised in sub-groups (of approximately 30 students) to ensure good interaction between students and teachers. Thus, this system would be implementable with large class sizes (e.g., 300 students) by dividing the class into sub-groups of approximately 30 students. However, this approach requires a close coordination between teachers to ensure that all students receive the same informations. In addition, this approach requires that the students should spend, outside the lectures, between 30 h and 60 h of work in autonomy or in team. Finally, this approach requires that the students have good skills in mathematics and mechanics.

6 Conclusions

The paper presents the soil mechanics course for the Department of Civil Engineering and Construction students at the ENPC. Students attend this course during Semester 3 while joining the Department with an excellent mathematics, physics and mechanics background. The following conclusions can be addressed.

- It is important to emphasise the essential concepts of soil mechanics such as phase relations, Terzaghi effective stress, Darcy law, consolidation, settlement, oedometer test, shear strength, and triaxial compression test. The Geotechnical Triangle (Burland, 2008) should be used to clarify the “reality” and the “theory”.
- To prepare future engineers for new challenges in a changing world, the introduction of poromechanics and literature review projects helps the students go beyond the standard concept of soil mechanics and better understand the role of soil mechanics in various contexts.

- Conducting a constitutive modelling project motivates the students to master the essential models in soil mechanics, better understand soil mechanical behaviour, and be better prepared to use finite element software in their future activities.
- Close interactions are essential when designing the soil mechanics course and the other geotechnical engineering-related courses to accompany the students in their future path. A compulsory course on LCA during the last year of studies, applied to a technical design project, invites the students to adopt a systemic point of view.

References

- Airey, D. & Miao, G. (2016). Why Critical State Soil Mechanics should be taught to all civil engineers. SFGE 2016 - Shaping the Future of Geotechnical Education. International Conference on Geo-Engineering Education – TC 306.
- Atkinson, J. (2008). What should geotechnical engineers be able to do and how should they acquire these skills? Education and Training in Geo-Engineering Sciences, Manoliu I., Radulescu, N. (Eds.), pp. 3-8, Taylor & Francis, London, UK.
- Burland, J.B. (2008). Personal reflections on the teaching of soil mechanics. Education and Training in Geo-Engineering Sciences, Manoliu I., Radulescu, N. (Eds.), pp. 35-48, Taylor & Francis, London, UK.
- Ledesma, A. (2025). Discussion of “Teaching Modern Soil Mechanics”. Soil. Rocks, 48(1), e2025007424.
- Macedo, J. & Pinho-Lopes, M. (2024). Key concepts in soil mechanics: simple hands-on and team-based strategies to promote active learning. Proceedings of the XVIII ECSMGE 2024. <https://doi.org/10.1201/9781003431749-101>.
- Maranha das Neves, E. (2024). Teaching modern soil mechanics. Soil. Rocks, 47(2), e2024006823.
- McDowell, G.R. (2001). A Student-centred Learning Approach to Teaching Soil Mechanics. Int. J. Engng Ed. Vol. 17, No. 3, pp. 255-260.
- Santamarina, J.C. (2015). (What) To teach or not to teach– that is the question. Geotechnical Research, 2, 4, 135-138. <http://dx.doi.org/10.1680/jgere.15.00004>.
- Tang, A., Hughes, P., Dijkstra, T., Askarinejad, A., Brenčić, M., Cui, Y., Diez, J., Firgi, T., Gajewska, B., Gentile, F., Grossi, G., Jommi, C., Kehagia, F., Koda, E., ter Maat, H., Lenart, S., Lourenco, S., Oliveira, M., Osinski, P., Springman, S., Van Beek, V. (2018). Atmosphere–vegetation–soil interactions in a climate change context; impact of changing conditions on engineered transport infrastructure slopes in Europe. Quarterly Journal of Engineering Geology and Hydrogeology, 51(2), 156-168. <https://doi.org/10.1144/qjegh2017-103>.
- Wesley, L. (2015). (What) To teach or not to teach – from theory to practice. Geotechnical Research, 2, 4, 139-147. <http://dx.doi.org/10.1680/jgere.15.00005>.

Authors’ bios

Anh Minh Tang, École nationale des ponts et chaussées (France)

Anh Minh Tang is a Research Director at the “École nationale des ponts et chaussées”, ENPC. He graduated from the National University of Civil Engineering (Vietnam) in 2001 and completed his PhD in geotechnics in 2005 at the ENPC. His Habilitation (HDR, accreditation to supervise research), completed in 2012 at Université Paris-Est (France), was on the behaviour of the soil under coupled thermo-hydro-mechanical loading and its applications in energy and environment. His research interests include unsaturated soils, geological storage of radioactive waste, soil-atmosphere interaction, geothermal energy, and gas hydrates. He teaches “Soil mechanics” and “Geotechnical design” and supervises projects undertaken by students at various levels.

Jean-Michel Pereira, École nationale des ponts et chaussées (France)

Jean-Michel Pereira earned his PhD in Civil Engineering in 2005 and achieved his Habilitation (HDR, accreditation to supervise research) in 2014. His research focuses on geomechanics, with

a particular interest in energy production challenges, including energy geostructures, geological storage of carbon dioxide, and radioactive waste disposal. As a professor at the École nationale des ponts et chaussées, he teaches "Soil Mechanics" and "Geotechnical Design."

Fahd Cuira, Setec (France)

Graduate Engineer from Ecole Polytechnique and Ecole nationale des ponts et chaussées. He specialises in soil-structure interaction and soil improvement for heavy and complex structures. He authored several calculation software marketed by Terrasol in France and abroad. Since 2018, he has been in charge of the course on the design of geotechnical structures at Ecole nationale des ponts et chaussées. From 2015 to 2023, he was the Scientific & Technical Director of Terrasol and has been the CEO since 2024.

Matthieu Vandamme, École nationale des ponts et chaussées (France)

Matthieu Vandamme is a researcher at the "École nationale des ponts et chaussées", ENPC. He graduated from Ecole Polytechnique (France) in 2002 and from Ecole nationale des ponts et chaussées in 2004. He completed his PhD in Civil Engineering in 2008 at Massachusetts Institute of Technology (MA). His Habilitation (HDR, accreditation to supervise research), completed in 2019 at Université Paris-Est (France), was on the poromechanical behaviour of cement-based materials and geomaterials. His research interests include the mechanics and physics of porous solids, cement-based materials and geomaterials, in-pore physical processes and time-dependent deformations. He teaches "Mechanics and physics of porous solids" at the graduate level and "Porous materials for construction, energy and environment" at the undergraduate level. Since 2022, he has been the vice-head of the Department of Civil Engineering and Construction at ENPC.

***Coursework: Laboratory, Field,
Project-based,
Numerical Methods***

Running remote hands-on laboratory classes in soil mechanics

D. Airey & J. Zhu

The University of Sydney, Sydney, Australia

david.airey@sydney.edu.au, jiale.zhu@sydney.edu.au

ABSTRACT: During the Covid pandemic students were not allowed to attend laboratories in person for two years. The laboratory component of the introductory soil mechanics course was adapted by introducing exercises that students could perform in their kitchen in addition to providing data and video of the conventional laboratory classes. The paper will briefly explain how the five exercises, classification, compaction, flow, compression/consolidation and shear box were adapted for remote students. Significant components of the classification, compaction and flow experiments were conducted by students at home in their kitchens. The paper will describe these home experiments, discuss the challenges and provide reflections on the experience.

Keywords: Laboratory Classes, Remote Learning, Engineering Education

1 Introduction

The COVID pandemic resulted in lockdowns and students being unable to attend university classes. The short notice presented a major challenge for laboratory work with most courses opting to either cancel any laboratory component or to provide video demonstrations in their place. This paper discusses an alternative approach in which components of the laboratory exercises were completed at home making use of commonly available pieces of equipment and materials.

As will be discussed this resulted in a significant increase in time commitment for the teaching staff and thus the reasons for continuing to offer laboratory work in this manner need justification. There is extensive literature and debate on the value of laboratory work in engineering and various authors have tried to identify the goals and benefits. Feisel and Rosa (2005) summarised this work and identified 13 fundamental objectives. Of these five are relevant to laboratory classes in the introductory soil mechanics course that is considered here, these are: using appropriate instrumentation; identifying strengths and limitations of theoretical models; collecting, analysing and interpreting data; communicating both orally and in writing about laboratory work, and sensory awareness. In engineering education more broadly some form of experimentation using physical systems is considered essential to enhance understanding of abstract concepts, increase student engagement and to introduce professional practice and skills (Lindsay & Good, 2005), and it is often mandated by accreditation authorities. In geotechnical engineering the importance of familiarity with materials and routine procedures is often stressed, but for most civil engineering students this is less important than improved conceptual understanding and making soil mechanics "real" (Airey et al., 2012). The ability of remote laboratories and simulations to meet the learning objectives of laboratory work has been questioned, with a study by Lindsay and Good (2005) concluding that alternatives to in-person laboratory classes lead to different learning outcomes, with some learning outcomes being improved at the expense of degradation in others.

Remotely performed experiments are not new, they have been offered for many years as part of open learning/distance education courses, but the motivation has been primarily to satisfy course requirements rather than on the grounds of learning. In this approach students are generally provided with specially prepared equipment and materials to allow the experiments to be performed remotely.

This has the disadvantage that it can be costly to provide the required materials, particularly if large cohorts of students are involved.

Remotely accessed experiments, where the equipment is housed in a university laboratory, have become more common recently because of the improved access, speed and reliability of internet resources. The inability to access physical laboratories during the COVID-19 pandemic has further increased interest in remote laboratories, spurring consideration of how to adapt existing exercises to a remote mode (Bhute et al., 2021). A COVID driven success with mailed 'at-home' geotechnical lab kits was reported by Stypulkowski et al. (2022), who found that more than 90 % of students preferred hands-on kit activities to data-only tasks. Alternatively, the laboratory activities can be changed, for example by using videos of the experiments and quizzes, to achieve the learning objectives in some other way (García-Ros & Alhama-Manteca, 2023). Videos showing equipment and procedures of standard soil mechanics tests are widely available and a useful compilation was produced by Geoengineer.org ("n.d."). However, videos on their own are limited in that they do not require active involvement of the learners, they are unable to provide the sensory awareness and there is no physical interaction with machines and sensors. It has also been suggested that students do not obtain an understanding of experimental limitations without the hands-on experience.

Another approach that removes the need for physical experiments is to make use of simulations and other interactive learning modules (ILMs). In geotechnical engineering education triaxial test simulators have been developed (Penumadu et al., 2000; Budhu, 2000) and ILMs have been used to supplement laboratory exercises (Jaksa, 2012). These simulations permit virtual laboratory exercises to be conducted which can be an alternative to physical experiments when equipment is unavailable because of lack of space, funds or equipment failure. Well-designed simulations can also provide a richer experience allowing students to explore more options than in a time constrained physical experiment. However, simulations also have limitations and challenges: to have a positive impact the simulation must resemble reality and be firmly grounded in rich pedagogy; the user interface must be intuitive and easy to use, so that time is spent learning the discipline concepts rather than navigation (Budhu, 2000); and these resources are time intensive to develop and have a short life due to constantly changing computer systems and software (Jaksa, 2012).

Remote laboratories that can be performed virtually have been developed in other branches of engineering and science, but they appear to be underdeveloped in civil engineering and geotechnical engineering. The nature of typical soils and the challenges of soil preparation act against remote laboratories. The only exception appears to be in centrifuge testing (El-Shamy et al., 2013) where the cost of the facility has encouraged academics to explore sharing of the equipment with students at remote sites.

The ability to adapt laboratory classes depends not only on the learning objective but also the type of activity. For example, in the soil mechanics laboratories the hands-on experience is an important part of the classification and compaction experiments. In other cases, such as consolidation and shear box the manual operation is less significant, and the task is primarily one of data collection, analysis and interpretation.

Another factor that was significant in the decision to attempt the remote laboratories was the timing. In the first year where COVID-19 restrictions were put in place the introductory soil mechanics course had been set up and timetabled as normal. This meant that all students were timetabled to take 5 laboratory classes in small groups of 10 people. A decision was made to continue with the laboratory program and as the students were prevented from attending the laboratory, for the experiments to be performed remotely. As obtaining familiarity (sensory awareness) with soil materials is one of the key learning objectives it was also decided to explore how some of the simple experiments could be performed from home without requiring any material or equipment to be provided. This paper explains the standard laboratory procedure and resources and then how these were adapted for remote learning.

In the first year with COVID restrictions staff were able to access the laboratory throughout the semester and restrictions for students eased halfway through the semester, although a significant cohort of international students experienced all the laboratory classes remotely. In the second year there was a complete lockdown, unexpectedly, shortly before the start of the semester and all staff and students were remote. As in the previous year the course had been timetabled with the small group laboratory sessions, and it was decided to repeat the remote experience from the previous year, the main difference being that all staff and students were remote for the entire semester.

2 Original Laboratory Design (Pre-Pandemic)

Before the transition to remote learning, soil mechanics laboratory sessions followed a structured format. Each semester, students completed five key experiments, each illustrating a fundamental aspect of soil behaviour. The laboratory sessions lasted two hours and were conducted in small groups, allowing students to directly engage with the equipment and materials. Each experiment follows a structured learning sequence, which has been designed to maximise the learning outcomes (Airey et al., 2012).

First, students completed pre-lab preparation, which involved reading background material, reviewing relevant theories, and completing a quiz to ensure they understood the experiment's objectives. During the hands-on session, students performed the tests under supervision, collected data, and observed soil behaviour. A key part of this process was the use of a worksheet, which helped students connect theoretical knowledge with practical observations. The worksheet provided structured guidance, prompting students to record experimental data, perform calculations, and compare results with expected outcomes. By systematically working through these steps, students were able to reinforce their understanding of soil behaviour while developing analytical skills. To complete the session, they processed their data, compared results with theoretical expectations, and discussed any discrepancies. A subset of students was assigned to write a formal report analysing the experiment and discussing its significance in engineering practice. Physical presence in the laboratory was crucial. It allowed students to handle soil samples, observe changes in texture and consistency, and operate testing equipment. The sensory aspects of laboratory work, such as feeling how moisture affects soil plasticity or how compaction changes soil density, are difficult to convey through theoretical instruction alone.

Each of the five core experiments demonstrated a different soil property and its significance in geotechnical engineering. This paper focuses on the three experiments which were modified to perform at home: soil classification; soil compaction, and permeability measurement.

The classification laboratory focused on identifying soils based on their particle size and plasticity. This was achieved using a combination of sieve analysis, the hydrometer method, Atterberg tests for liquid and plastic limit, and fall cone method for liquid limit determination. The results were used to classify two soils (SP and MH) according to the Unified Soil Classification System. To enhance the understanding of existing practice for liquid limit testing, the fall cone method was used alongside the Casagrande test. This method involved dropping a weighted cone into a prepared soil sample and measuring penetration depth, providing a more precise and repeatable determination of soil liquid limit. By comparing results from different techniques, students gained a deeper understanding of soil plasticity and how variations in testing methods affect classification outcomes.

The compaction laboratory demonstrated the relationship between moisture content and soil density. In this class, students conducted Standard and Modified Proctor tests to determine the maximum dry density of a silty clay at different moisture contents. By plotting dry density against moisture content, they could determine the optimum water content for compaction. Students physically compacted soil samples using standardized procedures and observed how moisture influences the compaction process and soil appearance.

The flow tank laboratory comprised two parts, a visual representation of groundwater movement through a dam, reinforcing students' understanding of flow nets and seepage through soil and measurement of the permeability of the sand in the flow experiment using a falling head permeameter. Only the falling head permeability experiment was modified. In the standard laboratory the permeameter test is repeated multiple times with sand at different relative densities and results analysed to produce a plot of permeability against void ratio. Since different soils exhibit widely varying permeability, students gained an understanding of how sandy soils drain quickly and of the dependence of this on soil type and density.

Additional laboratory classes in the course included oedometer and shear box testing. The oedometer test introduced fundamental concepts of soil settlement and consolidation by measuring how soil compresses under different loading conditions. The shear box test allowed students to determine soil shear strength parameters including friction angle and apparent cohesion. While these experiments played a key role in the broader curriculum, they were not modified in the remote learning transition due to their need for laboratory-grade equipment and instrumentation.

Each of these experiments reinforced the relationship between soil properties and engineering design. Moisture content, particle size, and compaction all influence the strength and stability of soil in construction projects. Through direct experimentation, students observed how external forces affect soil deformation and failure. They also learned how variability in soil properties requires careful site-specific

testing in engineering projects. The next section describes how the laboratories were modified for remote learning while attempting to maintain the core educational objectives of these experiments.

3 Transition to Remote Learning

The shift to remote learning presented significant challenges for soil mechanics laboratory instruction. Geotechnical experiments rely on direct interaction with soil samples, precision instruments, and controlled testing conditions, all of which are difficult to replicate in a home environment. Without access to physical labs, the course had to be restructured to ensure that students could still engage with the material and meet learning objectives while using household materials and remote instruction. A key priority in this transition was to maintain as much of the pre-COVID framework as possible. This included keeping the same flow, procedures, and worksheets to ensure continuity and minimise disruptions. The decision to retain the worksheet provided structure to the remote experiments, but it also posed challenges, as students had to rely on their own judgment in executing tests and interpreting results as the worksheets were not updated to reflect the changes in procedure.

To ensure students remained engaged and gained meaningful experience despite working remotely, the course adopted a structured three-component approach as shown in Figure. The first component was home-based practical work, where students performed simplified versions of the experiments using household materials. This ensured they retained some hands-on experience even without laboratory-grade equipment. The second component was instructor-led Zoom sessions and recorded videos, which covered both the original lab-based experiment and the modified home-based versions. These interactive sessions allowed students to observe standard lab procedures while engaging in discussions and asking questions in real time. The third component was data analysis and report writing. In common with the standard process all students were required to submit their filled in worksheets for sign off that the laboratory requirements had been completed. As some modifications to the experiments had been made, but not to the worksheets, this required clear communication of expectations to the students before the online sessions finished. For the subset of students required to write up a formal report real soil datasets were provided for analysis since many students struggled to obtain reliable measurements from their home experiments. This ensured that students worked with scientifically valid data while still reflecting on their own experimental observations. By structuring each experiment within this three-component approach, students maintained a level of engagement similar to the in-person lab sessions. The worksheet remained a core element of the course, guiding students through each stage of the experiments.

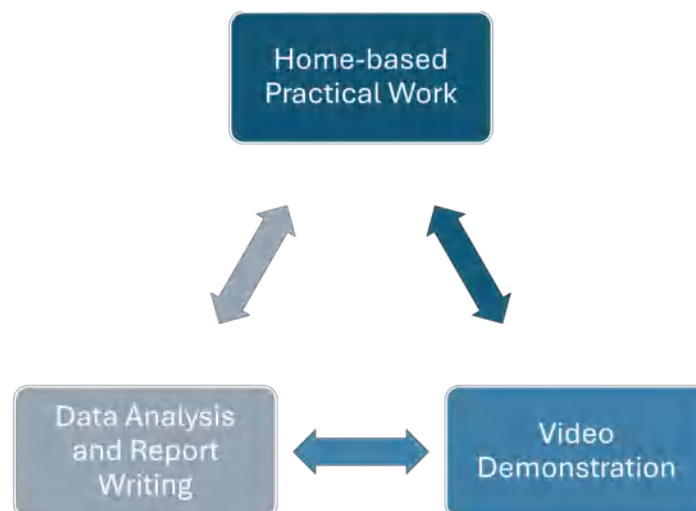


Figure 1. Three-component approach to remote lab design

The equipment and materials required for the at-home component of the experiments are listed in the Appendix. Most of these items could be purchased or be delivered from local retail shops. The main concerns were whether students would have access to a suitable balance, measuring to 0.1 g, and to a microwave. Prior to the start of the semester the possibility of using one's mobile phone as a balance

was explored as there are several apps claiming the ability to measure to 0.1 g. These apps were not very stable but they were recommended as a fallback for anyone without a balance. As it turned out most students appeared to have access to accurate balances and we are unaware of anyone having to use a phone app. Microwaves were widely available and only a couple of students each year reported having to use a conventional oven.

For the classification experiment, students needed to differentiate between fine and coarse-grained materials and analyse plasticity. Various common materials were considered to determine the best substitutes for soil. Food products have the advantage of being readily available and they have a wide range of properties that can be used to illustrate soil behaviour and enhance student intuition and scale awareness (Fiegel & Derbidge, 2015). Rice flour and rice were ultimately chosen as the most suitable replacements for fine- and coarse-grained soils. Rice flour, with its finer particles, behaved somewhat similarly to silt, while rice mimicked coarse sand. Although these materials could not perfectly replicate real soil, they allowed students to observe fundamental classification concepts. As part of the particle size analysis, students used a kitchen sieve to simulate standard sieving procedures. During live Zoom sessions, the instructor demonstrated sieving rice flour through a standard stack of sieves and performing a hydrometer test, again using the rice flour, and made the results available to the students to complete the worksheets. The worksheet guided students through drawing a grading curve using their own rice and rice flour mixtures. While this was intended to be a straightforward exercise, many students struggled with the inclusion of the at home sieving step due to a lack of understanding of the classification process. It was initially planned to conduct a hydrometer sedimentation test at home and a crude hydrometer was constructed out of readily available equipment, but it was decided not to use this as it was considered too difficult for students to construct and to take any meaningful measurements. The students writing a report were provided with pre-recorded data from sieving and hydrometer tests of a silty sand. In their reports, they were required to compare their rice flour results with real soil test data from the instructional videos, but very few critically engaged with this comparison.

The second part of classification experiment involved testing for plasticity. A rough approximation of the liquid limit (60%) for rice flour was provided for sample preparation. Students mixed the rice flour and water which was to be placed in a small cup or similar sized container. A fall cone test was then performed using a custom-built cone penetrometer. A comparison between the standard laboratory cone penetrometer tip and the home-made version is shown in Figure. Students constructed the device using easily accessible materials, including a plastic cup, a pencil, Blu Tack, and a piping bag tip with an approximately 30-degree cone angle. The device was weighted to match the standard 80 g mass of a laboratory penetrometer. By dropping the weighted penetrometer into the sample, students could roughly measure the penetration depth after which they had to take a small sample for moisture content measurement. This used the microwave method as this provided a faster means of removing water from the rice flour samples, though it required careful monitoring to avoid overheating. Leaving the samples in the microwave for too long or using excessive power resulted in charring of the rice flour, which

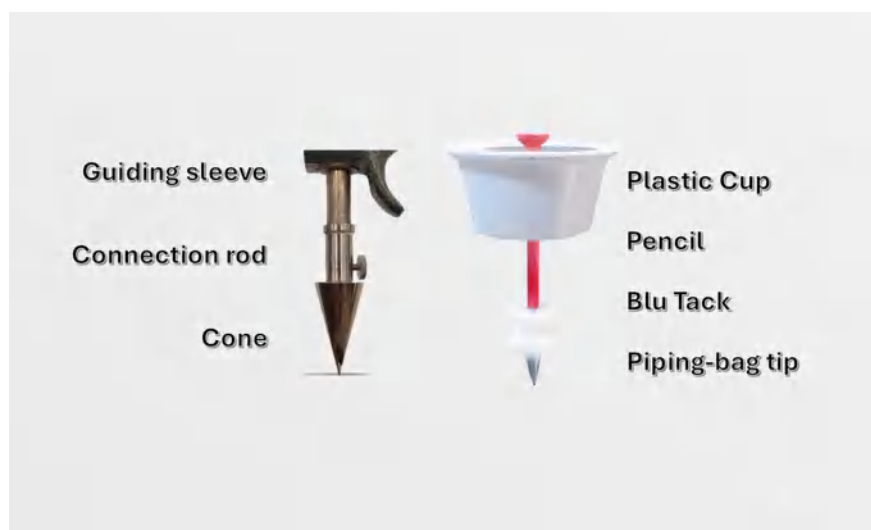


Figure 2. A comparison between a standard cone penetrometer and a home-made cone penetrometer

affected the accuracy of the measurement. To mitigate this risk, students were instructed to use short heating intervals and observe the changes in sample mass to ensure proper drying. The students also found that using too much rice flour did not allow drying out, whereas too little rice flour resulted in unreliable measurements. A second point for the moisture content, penetration graph was then required to estimate the liquid limit, taken to occur at 20 mm penetration. If the penetration in the first test was < 20 mm the students were asked to add water and if it was > 20 mm to add more rice flour, remix and repeat the experiment. The final stage was to roll out the rice flour to form a 3 mm diameter thread to estimate the plastic limit. However, because commonly available rice flour was predominantly coarse silt sized, students struggled to form the standard 3 mm diameter thread revealing the rice flour to be non-plastic. While the homemade setup lacked the precision of the laboratory cone penetrometer, it effectively demonstrated the principles and procedures behind the liquid and plastic limit determinations. Despite its challenges, this exercise still helped students understand the broader definition of soil plasticity. This approach reinforced key concepts by allowing students to observe the relationship between moisture content and soil strength, despite the constraints of working at home. Additionally, students could compare their results with video demonstrations of the laboratory fall cone test, ensuring they still developed an understanding of the method and its practical significance in soil classification.

For the compaction experiment, students compacted rice flour inside small containers, measuring the change in volume before and after compaction. Rice flour has a specific gravity of approximately 1.45 and milled rice flour has a loose bulk density in the range 0.69–0.91 g cm⁻³ (Chandra & Samsher, 2013), similar to that of other fine-grained minerals. A significant issue arose from the assumption that all students would have access to a coffee cup or a similarly sturdy container. However, some students, particularly international students, did not have access to a suitable container as they were under quarantine, and many students used containers that were too flimsy to sustain strong compaction, making it difficult to apply much force. Where students had access to soil from a garden (not topsoil), they were encouraged to perform the compaction test with real soil rather than rice flour. Rather surprisingly very few students chose this option. For students using rice flour, moisture contents of 20%, 40%, 60% and 80% were suggested as suitable target values for mixing prior to compaction, and post compaction a small moisture content sample was taken for drying in the microwave. Unlike standard laboratory Proctor tests, where a rammer is used to apply controlled compaction energy, students relied on pressing or tapping motions, which introduced variability in their results. Nevertheless, despite the poor equipment and limited compaction most students obtained reasonable dry density versus moisture content responses enabling an optimum moisture content to be estimated as the response approached the zero air voids line. To ensure consistency in data analysis, students were provided with real soil compaction data to use in their reports.

For the permeability experiment, students constructed a falling head permeameter using a clear plastic water bottle with drainage at the bottom created by punching small holes in the bottle. A thin layer of rice was placed to act as a filter followed by a layer of rice flour. The mass and height of the rice flour were measured, together with the bottle diameter to enable the density and void ratio of the rice flour to be calculated. The bottle was then filled up with water and the water level measured over time. As it took about 60 minutes for the water level to drop other components of the laboratory were then conducted. This setup preserved the fundamental principle of the falling head test, allowing students to visualise how permeability functions. While waiting a flow tank demonstration was provided via Zoom. The instructor guided students through a live session, showing how the manometer readings change with position, and ink was injected to show live the flow lines, which the students had to trace out onto a diagram of the flow tank in their worksheets. Manometer readings were read out to the students, and students used this information to create a flow net, reinforcing their understanding of groundwater flow concepts.

The other two core experiments, consolidation with oedometer and shear box testing, were deemed impractical to replicate with simple household equipment, especially when students overseas struggled to find equipment such as coffee cups. As a result, students were shown video demonstrations of the standard laboratory procedures, with instructors providing detailed explanations of the process and expected outcomes. Values of measurements from previous years were provided for students to fill in the worksheets and perform the required data analysis and interpretation. In addition to the equipment and instrumentation challenges the decision to use video was dictated by the need to follow the existing procedures detailed in the worksheet and the pre-lab material, even though alternative instructional methods could have been considered.

Table 1 presents a concise comparison of each laboratory in its original and remote formats and indicates the extent to which the five targeted learning outcomes were achieved. The previously mentioned five learning outcomes adopted from Feisel & Rosa (2005) are: (1) instrumentation; (2) recognising limits of theory; (3) data collection/analysis; (4) communication; (5) sensory awareness.

Table 1. Key differences between in-person and remote laboratories and their learning outcomes

Experiment	Delivery mode	Core activity	Learning outcomes achieved	Learning outcomes compromised
Soil classification	In-person	Sieve & hydrometer tests; fall-cone & plastic/liquid limits with two real soils	• Instrumentation • Data collection/analysis • Sensory awareness	
	Remote	Kitchen sieve, rice/rice-flour grading; student made fall-cone; measure moisture content; video hydrometer data	• Data collection/analysis (partial) • Communication (worksheet/report) • Sensory awareness (partial)	• Instrumentation (precision)
Compaction (Proctor)	In-person	Standard & Modified Proctor hammering; density/moisture curve	• Instrumentation • Theory vs. data • Sensory awareness	• Compaction energy effect • Sensory awareness (partial)
	Remote	Hand-compacting rice-flour mixes in coffee cup; density plot	• Concept of moisture–density relationship • Data interpretation	
Permeability & Flow	In-person	Falling-head test on sand at 3 densities; live flow-tank manometer grid	• Instrumentation • Theory vs. data • Sensory awareness	• Influence of density on flow
	Remote	Falling-head in bottle; Zoom flow-tank demo	• Concept of Darcy's Law • Data analysis	
Consolidation & Shear box	In-person	Oedometer loading with dial gauges	• Instrumentation • Time rate analysis • Mohr-Coulomb Theory	• Instrumentation
	Remote	Video demo; supplied data for analysis	• Concept of 1D consolidation and critical state soil mechanics • Data analysis	• Sensory awareness

Despite the transition to remote learning, the worksheet and structured framework were retained as part of the learning process. This decision ensured continuity in student engagement by providing a structured approach to data collection and analysis. However, keeping the worksheet also introduced challenges. In an in-person lab, students could seek clarification from instructors and peers, but in a remote setting, they had to work independently, which made troubleshooting more difficult. While alternative assessment formats could have been considered, the decision to retain the worksheet was based on its effectiveness in guiding students through the experimental process and reinforcing key learning outcomes.

The shift to remote laboratory learning introduced new challenges but also provided insights into how geotechnical instruction can be adapted for different environments. The next section will explore how differences in the years with remote learning affected student experiences and highlight key observations from these adaptations.

4 Reflections and Lessons Learned

The transition to remote laboratory learning provided valuable insights into both the strengths and limitations of online adaptations in geotechnical engineering education. While some aspects of the course were effectively maintained, others highlighted the challenges of replacing physical experimentation with digital resources and modifications at home. The remote format still successfully developed students' data analysis skills, with improved engagement in hands-on tasks, and provided a more individualised learning experience. However, challenges arose in maintaining effective communication, managing inconsistencies in student results, and ensuring that the broader conceptual understanding was retained. The shift also placed a significantly higher workload on instructors, as every student was individually monitored. While the overall learning outcomes were maintained, the coordination of remote labs required adjustments.

The material choice was a critical issue. It needed to be widely available, to be stable in water and consistent. Various flour products were considered before choosing rice flour. Some students sourced glutinous rice flour which did not behave like soil and the fineness and hence liquid limit of the flour varied between suppliers. Overall, the rice flour performed well, but further research is recommended to investigate other alternatives for anyone considering home experiments. Using foodstuffs assists with the sensory-awareness objective identified by Feisel & Rosa (2005) and as demonstrated by Fiegel & Derbidge (2015) can provide geotechnical analogues for a range of soil behaviours.

One of the key successes was that students appeared more engaged in the hands-on portion of the experiments. In previous years, classification tests were difficult to complete within a two-hour session due to time constraints and limited equipment. In contrast, the remote version allowed students to complete their hands-on work within the same timeframe. Unlike the in-person format, where five-student groups meant that not all students actively performed tasks, the remote setup ensured that each student conducted the full experiment independently while following live Zoom instructions. Although students were technically still part of a five-person group, the dynamic changed significantly, as each individual had to fully engage in conducting the experiment on their own rather than relying on a more confident peer to lead the process. For instructors, this setup meant that every student was under closer scrutiny, eliminating passive participation but significantly increasing the workload. With every student required to demonstrate their understanding individually through the worksheet submission, instructors had more opportunities to pinpoint specific areas of confusion, but the added supervision, additional zoom meetings, email correspondence and troubleshooting made coordination far more challenging.

Although students required less time to complete the experiments as less activities were involved, more time was spent explaining the broader context and ensuring students understood why rice flour and rice were chosen as substitutes for real soil. The classification experiment required additional discussion to help students relate the home-based experiment to real soil mechanics. Since the materials used were frictional in nature, the instructor needed to explicitly highlight how their behaviour still aligned with fundamental soil mechanics principles. These discussions were included at both the beginning and end of the experiment to reinforce the learning objectives. This additional conceptual explanation ensured that students were not only engaged with the physical tasks but also understood the underlying mechanisms they were studying.

Despite these efforts, communication over Zoom presented several difficulties. As is common in virtual environments, poor audio quality and the absence of non-verbal cues made it harder for students to fully grasp instructions. Many students also chose not to turn on their cameras, making it difficult for instructors to assess engagement and detect when students were struggling. This was particularly problematic in experiments where real-time troubleshooting was essential. In a physical lab, misunderstandings could be spotted and corrected immediately, but in the remote setting, many issues only became apparent at the end when students submitted worksheets with nonsensical data. This resulted in some students having to redo parts of the experiment to obtain usable results, leading to delays and additional sessions. Additionally, without visual engagement, instructors struggled to identify moments when students needed extra clarification, leading to repeated explanations and additional time spent reinforcing instructions.

The issue of inconsistent results across the cohort was another challenge. In classification experiments, this was partially mitigated by providing standardised soil data for analysis. However, students still conducted some measurements independently, such as coarse rice particle grading, leading to further inconsistencies. Some students attempted to bypass the challenge by using previous years' soil data

instead of conducting their own measurements. These cases were easy to identify, as reports were expected to compare rice flour results with real soil data from provided datasets. This emphasises the benefit of structuring assignments in a way that encourages genuine student engagement rather than reliance on past reports.

Students had mixed opinions on the laboratory classes, but generally they were more positive about the classes that used the kitchen experiments than when only videos were provided. Some students commented that they would prefer to do the exercises in the soils laboratory, but nevertheless the lab classes resulted in a better understanding of soil mechanics through providing a specific demonstration of the concepts. These exercises had an impact on the students, they were the only hands-on exercises the cohort experienced during COVID, and this was appreciated and commented on at their graduation. This mirrors the very positive response documented in Stypulkowski et al. (2022) for other at-home activities during this period.

The laboratory exercises were timetabled which is unusual for remote experiments where students are generally provided with resources and have the freedom to perform the experiments at a time of their choosing. As these changes were implemented during COVID the set times were not an issue, but if home-based experimentation is to be used then provision of clear guidelines and procedures to enable students to complete at their own convenience would be beneficial. For the laboratories that were not adapted, remotely controlled experiments could be developed. The convenience of operating equipment from home has been positively received by students in electrical engineering (López, 2021), but as noted earlier it is important for the internet platform to be simple, intuitive and easy to use. A similar approach could be explored for soil mechanics, where a hydraulic oedometer setup could be adjusted remotely, with students inputting values online and observing changes via a camera feed. While the cost of such adaptations may be too high to justify for short-term use, a virtual reality lab could provide a more accessible alternative. A VR-based system that can work on conventional flat screen could allow students to interact with simulated soil testing equipment, bridging the gap between tactile experience and theoretical understanding.

Although remote labs presented coordination challenges, they also demonstrated potential opportunities for future hybrid learning models. A combination of online pre-lab preparation, interactive remote components, and in-person experiments could provide a more flexible and comprehensive learning experience. To address communication issues, requiring cameras to be turned on during interactive sessions or incorporating more structured participation elements could help instructors better assess student engagement. Similarly, integrating virtual lab tools could enhance students' ability to visualise and interact with soil testing processes beyond video demonstrations. With these refinements, remote and hybrid labs could serve as a valuable complement to traditional geotechnical education, providing students with flexible yet effective hands-on learning opportunities.

5 References

- Airey, D., Cafe, P., Drury, H. (2012). The use of online resources to support laboratory classes in soil mechanics. *Shaking the Foundations of Geo-engineering Education*, McCabe, Pantazidou & Phillips (eds), pp 113-120, Taylor & Francis Group, London, UK.
- Bhute, V.J., Inguva, P., Shah, U., Brechtelsbauer, C. (2021). Transforming traditional teaching laboratories for effective remote delivery—A review, *Education for Chemical Engineers*, 35, pp. 96-104.
- Budhu, M. (2002). *Virtual Laboratories for Engineering Education*. Int Conf Eng Educ, 1.
- Chandra, D. S., Samsher. (2013). Assessment of functional properties of different flours. *African Journal of Agricultural Research*, 8(38), 4849–4852. <https://doi.org/10.5897/AJAR2013.6905>
- El-Shamy, U., Abdoun, T., McMartin, F., Pando, M. A. (2013). Integration of centrifuge testing in undergraduate geotechnical engineering education at remote campuses. *European Journal of Engineering Education*, 38(3), 268–280. <https://doi.org/10.1080/03043797.2013.794199>
- Feisel, L.D., Rosa, A.J. (2005). The role of the Laboratory in Undergraduate Engineering Education, *Journal of Engineering Education*, 94(1), pp.121-130.

Fiegel, G. L., Derbidge, N. (2015). Introducing Soil Property Evaluation in Geotechnical Engineering – Some Food for Thought. 122nd ASCE Annual Conference & Exposition, Seattle, WA.

García Ros, G., Alhama Manteca, I. (2023). Online laboratory practices and assessment using training and learning activities as teaching methodologies adapted to remote learning. Student satisfaction and improved academic performance. *Heliyon*, 9, e19742. <https://doi.org/10.1016/j.heliyon.2023.e19742>

Jaksa, M. (2012). Interactive learning modules in geotechnical engineering, *Shaking the Foundations of Geo-engineering Education*, McCabe, Pantazidou & Phillips (eds), pp 131-136, Taylor & Francis Group, London, UK.

Jaksa, M., Airey, D., Kodikara, J., Shahin, M., Yuen, S. (2012). Reinventing Geotechnical Engineering Laboratory Classes, *Shaking the Foundations of Geo-engineering Education*, McCabe, Pantazidou & Phillips (eds), pp 137-142, Taylor & Francis Group, London, UK.

A list of videos on laboratory testing to support online instruction ("n.d."), *Geoengineer.org*. <https://www.geoengineer.org/education/laboratory-testing/a-list-of-videos-on-laboratory-testing-to-support-online-instruction>

Lindsay, E., Good, M. (2005). Effects of laboratory access modes upon learning outcomes, *IEEE Transactions on Education*, 48, 619-631.

López, A. (2021). RLAB-UOC: A remote laboratory for performing experiments with real electronic and communications equipment. *Universitat Oberta de Catalunya*. <https://www.uoc.edu/en/news/2021/180-computing-lab>

[Penumadu, D., Zhao, R., Frost, D. \(2000\)](#). Virtual geotechnical laboratory experiments using a simulator, *International Journal for Numerical and Analytical Methods in Geomechanics*, 24(5), pp.439-451.

Stypulkowski, A. L., Huntoon, J., Burns, S., Huang, H. (2022). Geotechnical Engineering Lab Course Virtual Instruction Methods: A Response to Covid-19. *ASCE Geo-Congress 2022, GSP 336*, pp 453-462. <https://doi.org/10.1061/9780784484067.045>

Van den Beemt, A., Groothuisen, S., Ozkan, L., Hendrix, W. (2022). Remote labs in higher engineering education: engaging students with active pedagogy *Journal of Computing in Higher Education* (2023) 35, pp.320–340

Appendix

List of Equipment involved

Material	Classification	Compaction	Permeability
Microwave or Oven	✓	✓	
Digital kitchen scales	✓	✓	✓
Kitchen measuring cups	✓	✓	✓
Kitchen sieve – the sort used for sifting flour	✓		
Mixing bowl	✓	✓	✓
Spatula	✓	✓	✓
Access to Water	✓	✓	✓
Small container to hold wet mixture (5cm diameter x 5cm tall)	✓	✓	✓
Small microwave/oven safe plastic container	✓	✓	
Oven Gloves	✓	✓	
Cone penetrometer (Pencil, piping bag tip, Blu Tack, weighted to 80g)	✓		
Ruler	✓	✓	✓
Smooth impermeable bench surface	✓	✓	✓
1 kg Rice Flour (must be rice flour, not ordinary wheat flour)	✓	✓	✓
Larger grained foodstuff (rice, dried lentils, etc.)	✓	✓	✓
Plastic water bottle (for permeability test)			✓

Authors' bios

David Airey, University of Sydney (Australia)

David Airey is a professor of Civil Engineering at the University of Sydney who specializes in experimental geomechanics. He holds undergraduate, Masters and PhD degrees from the University of Cambridge. He has made contributions to the understanding of soil testing, soil and rock behaviour, contaminant migration in soil and rock and foundation design. He currently has students exploring Intelligent Compaction, Foundation re-use, Solar farm piles, Unsaturated soil dynamics and Offshore slope stability. He has a passion for soil mechanics and its teaching and has contributed to all the international geotechnical engineering education conferences since 2008. He is currently deputy chair of TC306 and is involved with an Australia-New Zealand team providing guidance on the education and training of geotechnical engineers.

Jiale Zhu, University of Sydney (Australia)

Jiale Zhu, also known as Joey, is a post-doctoral researcher at the University of Sydney, specialising in geotechnical engineering. His research focuses on unsaturated soil liquefaction and sustainable root reinforcement for soil stability. Joey has extensive experience in teaching civil engineering and mentoring students, alongside active involvement in professional associations. He also serves as the president of the New South Wales Chinese Students and Scholars Association, organising academic and cultural events.

An international coursework on the design of a retaining structure and a building competition

V. Dimitriadi¹, D. Barreto¹, J. Leak², A. Arnold³ & H. Vogt³

¹Edinburgh Napier University, School of Computing and the Built Environment, Edinburgh, UK
V.Dimitriadi@napier.ac.uk, D.Barreto@napier.ac.uk

²University of Strathclyde, Department of Civil & Environmental Engineering, Glasgow, UK
james.leak@strath.ac.uk

³Lucerne University of Applied Sciences and Arts, School of Engineering and Architecture, Lucerne, Switzerland
andre.arnold@hslu.ch, hansjoerg.vogt@hslu.ch

ABSTRACT: A Collaborative Online International Learning (COIL) initiative carried out between Edinburgh Napier University (ENU) and Lucerne University of Applied Sciences and Arts (HSLU) is presented. The initiative included the design of a soil-nailed/anchored/propped/reinforced earth retaining wall system supporting a sandy backfill, by building an analogue in the laboratory and subsequently the performance of a failure analysis. The objective was to develop an accurate prediction of the behaviour of the above geotechnical system, given detailed information regarding soil, boundary, and initial conditions, as well as the relevant geotechnical and structural loading. To address the coursework, students were encouraged to use any available empirical correlations for design purposes, in addition to the development of simple, accurate computer code for making predictions and/or other design/analysis calculations. Students significantly benefited from the project as they managed to visualise the different available retaining wall configurations and obtain valuable experience from their laboratory-based work. In addition, they had the opportunity to collaborate with students from another university and engage in meaningful discussions on comparing experimental results against empirical and/or analytical predictions.

Keywords: *Project-based learning, Coursework, Laboratory testing, Internationalisation, Learning by discovery*

1 Introduction

The structure of modern curricula in most engineering disciplines focuses on the development of technical (hard) skills, but also on the development of non-technical (soft) skills, especially in the final years of study. The development of non-technical skills often requires a less traditional teaching set up and the use of alternative teaching methods (Fry et al., 2009). For instance, learning in small groups is an efficient means of engaging students in their learning journey and promotes better communication amongst peers and the teaching team. Additionally, from a teacher's perspective, it also provides more time to cover questions and provide feedback to a smaller number of students.

Students' self-confidence, teamwork and interpersonal skills are further enhanced when small group teaching is infused by student-centred learning activities, such as project/laboratory-based projects. Their benefits have been studied by a wealth of researchers as reviewed by McKenna et al. (2018). It is widely accepted that such activities help students to significantly develop a variety of cognitive skills, as they conceptualise a problem, set learning goals, draw on existing knowledge, identify and evaluate available resources, create problem solving strategies, as well as monitor and self-regulate their own progress (Stolk & Harari, 2014). Students also have the opportunity to reflect on the validity of their

proposed solutions and maximise the learning value of the project (Stolk & Harari, 2014, Mills & Treagust 2003).

Moreover, through project-based learning activities students are experiencing engineering both from a theoretical and practical or better 'real-world' perspective, hence consider the work more relevant. They are then inclined to engage more in the activities and achieve deeper learning (Mills & Treagust, 2003). They further realise that basic theoretical concepts are important to understand and interpret laboratory processes and results, following a 'learning by discovery' principle (Hasselhorn & Gold, 2022), in which students learn independently, increase their self-efficacy and further advance their motivational skills. From another perspective, the introduction of laboratory-based projects in the curriculum is an essential attribute in professional accreditation reviews, as apart from enhancing student learning and elevating the student experience, they also enhance the reputation of the course.

In addition to the above, and particularly during the post-COVID era, module delivery on a Virtual Learning Environment (VLE) has dominated in the higher education and continues to have a strong presence, as it allows multiple forms of learning (individual or collaborative, distance or in person) to take place. E-learning tools generally allow for synchronous and/or asynchronous interaction and communication between students and/or between students and teachers (Fry et al., 2009). With regards to the latter, it is important to add that it is a vital element of a more internationalised provision of the curriculum, as students can be reached anywhere there is an internet connection (Fry et al., 2009). This attribute is becoming more evident in many programmes of study and responds to the need for graduates being able to join a global workforce. It also helps students broaden their horizons culturally and enhances their feeling of belonging to a greater community.

Within the above context, the Authors of the present paper, are presenting a collaborative online coursework initiative, which responds to modern teaching approaches and benefits students' learning on multiple levels. In the following sections, a detailed description of this collaboration is provided, supplemented by the relevant educational material. The paper concludes with a discussion on the lessons learned from running the project for two consecutive academic years.

2 Background

The joint coursework presented in this paper is founded on two main pillars, deeply rooted in the context of enhancing student learning in an international environment. The first is the concept of Collaborative Online International Learning (COIL). COIL, since its conception at the University of New York (SUNY), has been facilitating connections between students and academic members of staff in different countries and has been fostering collaborations and discussions as part of their learning journey (<https://coil.suny.edu/>). It is a means of providing students with opportunities to establish global collaborations and develop communication, language, digital and intercultural skills. It concurrently enables higher education institutions to enrich their programmes of study by offering opportunities for global engagement and internationalisation in a cost-effective way. In COIL courses students have the opportunity to interact with each other, build and create new knowledge. Through both individual and group reflection on the COIL experience students can learn the curriculum content but also learn how to collaborate more effectively in teams, while also developing intercultural, online and cooperation competencies.

Despite their high pedagogical value, COIL initiatives also present challenges, which have been highlighted in the literature. Differences in academic calendars, time zone differences between participating institutions and language barriers are only some of the operational challenges pointed out by Bauk (2019). In addition, setting up and running a COIL project entails a lot of additional work and effort, which is almost always based exclusively on the teachers' initiative, engagement and self-motivation. Hence, there is not extra workload formally allocated on a time management basis, which directly impacts the teachers' motivation to meaningfully engage in COIL initiatives (Kučerová, 2023). Moreover, participating members of staff need to be compatible in their approach to the project, commitment and time allocation, so that there is a balanced contribution to the project from both sides. Student engagement and participation has been highlighted as another challenge, which may negatively affect the end product of the initiative.

The second pillar of the initiative is based on the idea that the best way to learn, especially in engineering disciplines, is through a designing, building, and testing approach. The well-established concept of

Design, Build and Test (DBT), provides students with an educational experience that is engaging, motivational and increases their self-confidence and interest in learning (Elger et al., 2000). A DBT project needs to include a significant level of traditional theory, mathematical modelling and aspects of engineering practice, such as engineering drawing, teamwork, personal documentation and communication skills. It should be easy to implement with regards to required materials and resources, and to be transferable between instructors, so that a lot of the initial preparatory work is only performed once. Based on these characteristics, the DBT concept aligns well with the project-based learning framework presented earlier.

The teaching teams from Lucerne University of Applied Sciences and Arts (HSLU) and Edinburgh Napier University (ENU) joined forces and developed a coursework for their undergraduate (full time) civil engineering students relying on the above principles. The coursework was integrated to two relevant modules taught at the respective institutions of similar content and academic level.

3 COIL structure and project details

3.1 COIL structure

The collaborative online coursework was developed as part of two modules, taught at the two collaborating institutions. The module taught at ENU is entitled Transportation Geotechnics and Geoenvironmental Engineering, it is a 4th year module, and is focusing among others, on the analysis and design of gravity/embedded and reinforced earth retaining walls. The corresponding module taught at HSLU to 3rd year students is entitled Geotechnical Engineering – Advanced Course and it is focusing on the analysis and design of geotechnical structures. Students from both institutions are enrolled in Bachelor programmes in Civil Engineering and have appropriate background in soil mechanics and basic principles of geotechnical engineering design from modules taught and assessed in previous years of their respective programmes. In both institutions, the COIL coursework is incorporated in the main coursework that is typically contributing up to 20% towards the final mark of the corresponding modules. From a workload perspective the project accounts for 20% of the time dedicated to independent study, or around 35 hours.

The COIL coursework's focus is the design of a soil-nailed/anchored/propped/reinforced earth retaining wall supporting a sandy backfill and the prediction of its failure. Students are asked to develop an accurate prediction of the behaviour of their chosen geotechnical system, given detailed information regarding soil, boundary, and initial conditions, as well as the geotechnical and structural loading. To ensure that students from both institutions are aligned to the above objective, a set of lectures from HSLU and ENU staff is delivered right at the start of the COIL coursework. In the sequel, students, who are required to work in mixed ENU and HSLU groups of 3 – 4 people, perform some preliminary theoretical work on load prediction and start conceptually designing their chosen retaining system. In the construction phase, students spend time in the laboratory to build their chosen retaining system, which is then followed by the testing/loading phase, where they obtain their test results. Subsequently, students are required to submit a report, including their detailed design and analysis of the retaining system, also considering the test results of the model wall. This report is submitted following the load testing. The COIL coursework is concluded by a final discussion where students share their findings and results with other students as well as lecturers from both institutions. Through the different stages of the coursework, regular feedback is provided by the lectures of the two institutions.

3.2 Equipment and materials

The retaining structure is being built within an apparatus, also referred to as sandbox. The sandbox used at ENU, also presented in Figure 1a, is made of plywood, consisting of a base and three fixed vertical sides, which are stabilised by a tie bar. The fourth vertical side is a removable facing panel, that serves as a temporary boundary against which the wall is to be constructed. The sandbox has internal dimensions of 660 mm length, 457 mm width and 457 mm height. The final sand fill level in the box is 300 mm, which was the aimed height of the retaining system. The sandbox used at HSLU, also presented in Figure 1b, is made of 4 vertical sides and one floor side of plywood and has internal dimensions of 700 mm length, 500 mm width, 500 mm height. The final sand fill level in the box is 300 mm as well.

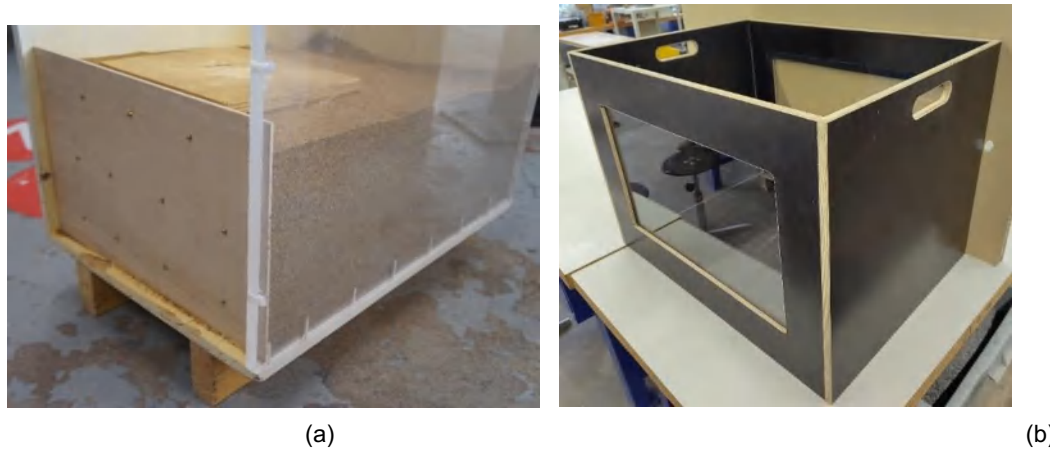


Figure 1. The sandbox used at (a) ENU and (b) HSLU

The backfill material used at ENU, is a clean, dry, Garside grade 10/18 Leighton – Buzzard silica sand. The backfill material used at HSLU is a sandy-gravelly material (2 – 4 mm) in a wet state. The particle size distribution curves for both materials are included in Figure 2. The bulk unit weight γ (kN/m³) and angle of friction ϕ (°) of the sand types used in the two institutions are also summarised in Table 1.

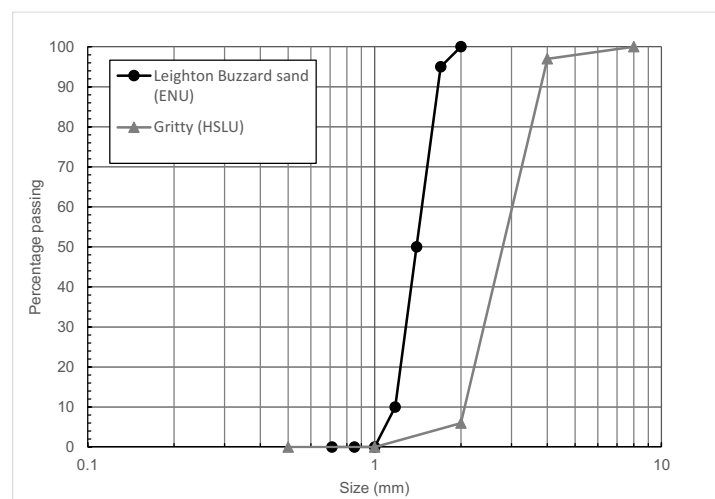


Figure 2. Particle size distribution for Leighton Buzzard sand (ENU) and gritty material (HSLU)

Table 1. Material properties from ENU and HSLU

Soil	γ (kN/m ³)	ϕ (°)
Leighton Buzzard sand (ENU)	15 - 17.3	31.7
Gritty (HSLU)	16.7	34

The wall materials are up to the designers' choice and have included materials such as cardboard, paper straws, string, sticky tape, spaghetti, marshmallows or anything else that could be acquired, tested and used at a relatively low cost. At ENU, the building and testing of the wall is performed by the lecturers and technicians, as opposed to HSLU, where students built and test their own models. This difference was due to operational and health and safety protocols that had to be in place. For compatibility and consistency reasons, in both universities, loading was performed using dead weights, which were placed on top of the backfill up to failure. Overall, 3 to 4 model walls were tested, following a selection based on the quality and completeness of the initial conceptual report, creativity and buildability.

Deliverables consist of two separate reports, namely a short report including the conceptual design of the retaining system and a longer submission with the detailed design and analysis, also considering the test results of the wall model. Students are expected to discuss details with their international and/or

local colleagues, hence encouraging peer communication. A final joint discussion with students and all involved staff is held at the end of the initiative, to highlight differences between experimental results and analytical/numerical solutions, as well as to share experiences from participating in the initiative.

As stated earlier, the initiative run for two consecutive academic years. Through this time, the structure of the project was slightly modified which helped optimise the benefits to the students and maximise the initiative's impact to students' learning. The specific COIL project has a duration of three weeks, with a typical structure of one meeting between students in the first week, followed by lectures to the HLSU students and ENU students on geotechnical topics by ENU and HSLU staff respectively, in weeks 2 and 3. In the second year, this structure was altered slightly to include the submission of students' conceptual designs of retaining systems. This significantly helped students to conceptualise their designs, have accurate estimates of required materials and have enough time to reflect on the construction aspects of their retaining walls.

For the purposes of sharing the available resources with the rest of the geotechnical community, a set of educational material is compiled and can be accessed from the TC306 Geoworld group [here](#). This includes the following:

- Project brief
- Pictures of different wall configurations
- Videos of testing
- Coursework submission samples.

3.3 Wall configurations and test results

Table 2 below, provides a selection of wall configurations that were tested at the two institutions along with material information and insights into the failure mechanisms. Appropriate reference to subsequent figures is made for each one of the presented configurations, to help readers visualise each solution.

Table 2. Selection of tested wall configurations

Solution name	University	Material information	Failure load	Comments
1. Cardboard with soil nails (Figures 3)	ENU	Cardboard (1.5 mm) reinforced with 2 rows of 4 soil nails made of bamboo skewers 230 mm in length and 3 mm in diameter.	Not recorded (Failure by pull-out)	Predicted failure load of 20 kgf was not reached, as wall failed under its own weight.
2. Cardboard with soil nails (Figure 4)	HSLU	Cardboard (3 mm) reinforced with 3 rows of 6 soil nails, made of bamboo skewers.	135 kgf	Predicted failure load around 19kgf. Difference in failure load between this and case No1 above, was attributed to high dilatancy due to angular soil grain, higher number of nails and thicker wall material
3. Gabion wall (Figures 5)	ENU	Square chicken wire (H:V 50 mm × 25 mm) filled with marshmallows (40 mm × 25 mm × 20 mm) and reinforced by standard jute rope (Ø 6 mm).	40 kgf	A very flexible wall. Predicted failure load of 30 kgf exceeded, but plenty of spillage was noted due to poor workmanship.
4. Wooden plate with soil nails (Figure 6)	HSLU	Wooden plate (10 mm) and Perspex material with soil nails constructed with cord, wrapped around wooden columns of the retaining wall, using polystyrene balls as anchors.	139 kgf	Target load of 54 kgf was exceeded, and failure was induced by the students.

The soil nails reinforced cardboard wall built at ENU, also presented in Figure 3, consisted of 1.5 mm cardboard reinforced with soil nails made from bamboo skewers. The cardboard was inclined at 5.7° from the vertical and was supporting a backfill of a height of 300 mm. Vertical spacing of the nails was 200 mm with the highest and lowest inclusions at depths 50 mm and 250 mm, respectively. The

horizontal spacing between the nails was 130 mm with a 33 mm gap between the nails and the edge of the sandbox. Skewers were fixed to 30 mm square bearing plates of 3 mm plywood. The bearing plates were drilled with 3 mm pilot holes and fixed to the skewer ends with hot glue. The pilot holes were drilled at 90°, resulting in an angle of 5.7° with respect to the horizontal. The predicted load of 20 kgf was not reached, as the wall failed in pull-out.

A similar reinforced retaining structure was tested in HSLU, presented in Figure 4. The cardboard was 3 mm in thickness, following the same inclination of 5.7°, reinforced with 18 soil nails in total, arranged over three rows of 6 nails per row. Similar bamboo skewers were used as soil nails. Horizontal spacing of skewers was 80 mm with a 50 mm gap between the nails and the edge of the sandbox. Vertical spacing of the nails was 50 mm, 200 mm and 250 mm, respectively, from the top. Skewers were fixed to the cardboard only with hot glue; hence no bearing plates were used. The failure load in this case was predicted at 20 kgf. Nevertheless, during testing the wall failed at about 135 kgf, which was explained on the basis of the number of nails, the thick wall material and the dilatancy of the fill material.

A gabion wall was further tested at ENU, which is presented in Figure 5. The gabion wall consisted of square chicken wire, filled with marshmallows and further reinforced with jute rope. The initial ultimate surcharge load prediction was 30 kgf. The ultimate mode of failure was due to the pull out of the reinforcement inclusions, in combination with the material spillage at the front of the wall. The latter was attributed to the difficulty in filling the chicken wire voids with the marshmallows.

The second configuration of a soil nailed wall from HSLU, presented in Figure 6, included using a 10 mm wooden plate, with its middle section cut out and replaced by a PVC material. The plate and PVC were anchored with cord/string which was wrapped around and against the retaining wall and anchored through polystyrene balls at the front. Soil nails were inclined at 10° and placed along two rows. Spacing information was not reported in students' submission. The target failure load was significantly exceeded and failure had to be induced by the students. Potential reasons for that were the wrapping of the cord around the wooden columns of the retaining wall.



Figure 3. Cardboard with soil nails configuration at ENU (a) front view of nail arrangement (b) loading set up.

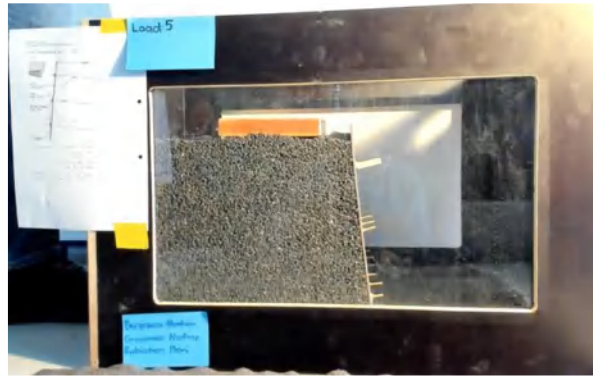


Figure 4. Cardboard with soil nails configuration at HSLU



(a)



(b)

Figure 5. Gabion wall tested at ENU (a) top view (b) front view at failure

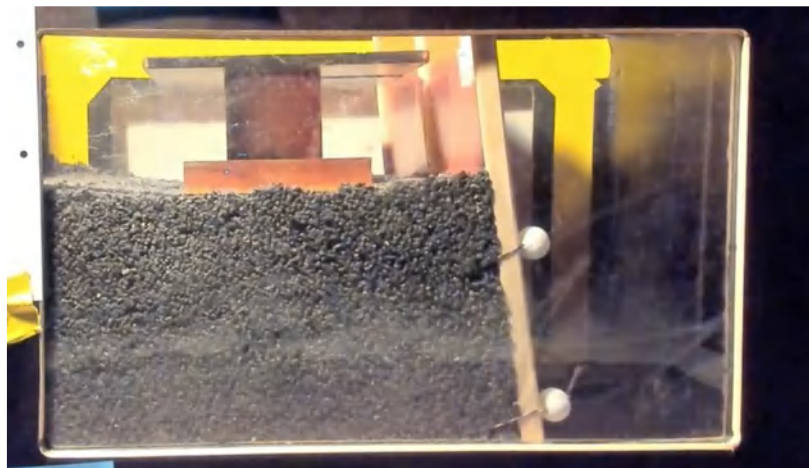


Figure 6. PVC plate with soil nails made of string with polystyrene balls as anchoring material

4 Lessons learned

In the present section the main lessons learned from the initiative are summarised. They are mainly focused on the teaching side of the initiative, although indicative student feedback is quoted in the end, which helps further appreciate the impact on the students' learning journey.

Based on the experience of the teaching team, a major topic that required careful planning before the rolling out the COIL, was the scope of work that needed to be the same between the two institutions and perhaps more importantly, it had to be aligned to the relevant modules' learning focus and outcomes. For instance, in the Geotechnical Engineering – Advanced Course module delivered at HSLU the main focus was soil nailing, therefore it was necessary to develop the COIL around this requirement and

always include at least one testing of a soil nailing set up. Additionally, it is important to ensure that the number of students participating from the two institutions are comparable. At ENU the student cohort was larger in both years, so to achieve comparable numbers the students went through a selection procedure organised by the teaching team. In the selection procedure students were required to submit conceptual designs of their retaining structures which were then evaluated based on originality, ingenuity and constructability. Note that the abovementioned selection procedure did not compromise the quality of student learning or the covering of the learning outcomes of the ENU-based module. That is because all students had to submit a failure analysis report as a deliverable of their coursework. From an assessment point of view, it was noticed that making the report submission part of the overall marking, led to increased engagement and this was evident in both years that the initiative run.

With regards to communication amongst ENU and HSLU students, it was observed that an almost 'forced' interaction between them was initially required in order to initiate a dialogue between the two groups. More specifically, the 'forced' interaction was in the form of a required weekly communication amongst students. The requirement was introduced in the second year of the initiative, given the hesitation and lack of engagement noticed in the first year. Especially at the start of the project this was deemed necessary and significantly enhanced student communication afterwards. For future initiatives it is worth exploring the organisation of ice-breaking activities even on an online basis to encourage student interaction.

As explained earlier, part of the students' work was to estimate quantities of the different construction materials before proceeding to the construction phase. However, in a couple of cases, miscalculations of material quantities led to incomplete construction of the retaining systems. This did not eventually allow the testing to proceed and highlighted the need for accurate estimates of the construction materials. This highlights the major role of project-based learning activities in students developing their critical thinking, autonomy and goal orientation.

Following the testing of the various types of retaining walls, it was noted that there was significant interest in a joint session to discuss results. The attendance was particularly high from both universities and students exhibited a high degree of engagement. This was also reflected in student feedback from ENU students, which was provided as part of the module's evaluation form at the end of the trimester and is quoted below:

Student A: The opportunity to work with the students from Lucerne on the retaining wall project was also a great benefit for students to improve skills such as, communication and networking that will benefit us for our future careers.

Student B: Cooperating with students from different universities and nationalities has given the opportunity to work in a new environment, allowing the team to overcome language barriers, time differences and creating accountability to the team and not just individual. Since the members of the team all have different academic and personal commitments, good organisation was required to set meeting times to discuss and plan out the project.

Student C: This project has given the team a chance to learn and/or enhance their skills that are required outside of university, in a working, engineering environment. Experience that will be essential for a successful post-graduate student.

5 Conclusions

In the present paper an online collaborative coursework project is presented and its benefits to both the teaching team and the students are analysed. The main conclusions are summarised below.

Good organisation and communication between the partner universities is crucial to the success of the initiative and constitute essential success ingredients of any future initiatives. It is also important to clearly communicate expectations, objectives and outcomes so that all involved parts are aware of the project and its demands. The design, building and testing sequence of a model significantly helps to experience soil mechanics and geotechnical engineering not only from a theoretical point of view, but also to realise that basic theoretical concepts are important to understand the load bearing behaviours and the design of geotechnical structures. The latter observation is fully aligned with the learning by discovery approach outlined in previous sections. Finally, it is precisely through these kinds of initiatives that students from different educational and cultural backgrounds interact, collaborate, get exposure to

different learning contents and eventually expand their perception of a truly global profession as it is the civil engineering one.

Acknowledgements

The HSLU authors would like to thank Movetia, the Swiss Agency for Exchange and Mobility for supporting the project COIL@HSLU.

References

Bauk, S. (2019). Collaborative Online International Learning Benefits Vis-À-Vis Concerns: An Empirical Study. *Montenegrin Journal of Economics*, 14(2), pp. 207-216.

COIL webpage at SUNY: <https://coil.suny.edu/>

Elger, D.F., Beyerlein, S.W., Budwig, R.S. (2000). Using Design, Build and Test projects to teach engineering. 30th Annual Frontiers in Education Conference. Building on a Century of Progress in Engineering Education. Conference Proceedings (IEEE Cat. No.00CH37135), pp. F3C/9-F3C13 IEEE, Kansas City, MO, USA

Fry, H., Ketteridge, S., Marshall, S. (2008). *Handbook for teaching and learning in Higher Education: Enhancing academic practice*, third ed. Routledge, New York, USA.

Hasselhorn, M., Gold, A. (2022). *Educational Psychology: Successful Learning and Teaching*, fifth ed. Kohlhammer, Stuttgart Germany.

Kučerová, K. (2023). Benefits and Challenges of Conducting a Collaborative online international Learning Class (COIL). *International Journal on Studies in Education*, 5(2), pp. 193 – 212.

McKenna, T., Gibney, A., Richardson, M.G. (2018). Benefits and Limitations of Adopting Project-Based Learning (PBL) in civil engineering education – a review. *Proceedings of EUCEET 2018: 4th International Conference on Civil Engineering Education: Challenges for the Third Millennium*, Turmo, J., Lozano-Galant J.A. (Eds.), pp. 171 - 180, International Center for Numerical Methods in Engineering (CIMNE). Barcelona, Spain.

Mills, J.E., Treagust, D.F. (2003). Using projects to teach structural engineering. *Australian Journal of Structural Engineering*, 4(3), pp. 211 – 220.

Stolk, J., Harari, J. (2014). Student motivations as predictors of high-level cognitions in project-based classrooms. *Active Learning in Higher Education*, 15 (3), pp. 231 – 247.

Authors' bios

Vasiliki Dimitriadi, Edinburgh Napier University (United Kingdom)

Dr Dimitriadi is a civil engineer with expertise in geotechnical earthquake engineering, working in the Higher Education sector in the UK since 2018. She is a Fellow of the Higher Education Academy since 2019. She is leading and delivering multiple geotechnical-related modules at Edinburgh Napier University at undergraduate and postgraduate level, addressing diverse and mixed student cohorts, such as mixed young and mature student groups, as well as international students of different educational and cultural backgrounds. As a result, she has obtained a deep understanding of the requirements and adjustments on a module level to cover different learning needs and styles. Through her teaching, she became interested in developing appropriate educational tools in order to address the challenges that students of diverse cohorts are facing. She is also interested in focusing on how the industry can feed into the module delivery to best form competent and well-rounded civil engineers. She is currently Programme Leader for the BEng in Civil Engineering and MEng in Civil/Civil & Transportation Engineering and leading quality assurance and accreditation procedures for both programmes.

Daniel Barreto Gonzalez, Edinburgh Napier University (United Kingdom)

Dr Barreto is Associate Professor of Geotechnical Engineering at Edinburgh Napier University where he has worked since 2009. He delivers geotechnical modules at both undergraduate and postgraduate level, both locally as internationally. He is a Fellow of the Higher Education Academy and has been nominated by students to various teaching awards. He is also contributing author for the textbook “Geotechnical Engineering Design” published by Wiley in 2015. As a (now Emeritus) member of the Royal Society of Edinburgh Young Academy of Scotland he mentored multiple high school pupils, as well as refugees in Scotland so they could better integrate as engineers into the Society. He is currently the Chair of the Open Network on DEM Simulations (ON-DEM) funded by COST. In addition to various ambitious research objectives, ON-DEM aims to promote the use of open-source DEM software by improving its learning curve by means of Training Schools, developing a best-practice and guidance handbook for DEM simulation, as well as various mentoring and outreach activities.

James Leak, University of Strathclyde (United Kingdom)

Dr Leak is a lecturer in civil engineering at the University of Strathclyde. He specialises in the delivery of geotechnical and engineering and has taught at multiple institutions including Edinburgh Napier and Shanghai Normal Universities. Dr Leak has been nominated for and received multiple teaching awards that were both student and institutionally led. Notably, he was shortlisted from over 240 teaching staff at Edinburgh Napier University for best lecturer in the staff recognition awards in 2024. He has worked with multiple external organisations including the Nuffield Foundation and Edinburgh Science Ceilidh to deliver science and engineering teaching to a broad range of audiences, including primary school children and refugees. Currently, Dr Leak is the secretary of the Scottish Universities Geotechnical Network and is working to further the teaching and research opportunities in the field of geotechnical engineering for all universities across the network.

André Arnold, Lucerne University of Applied Sciences and Arts (Switzerland)

Dr Arnold is a Professor of Geotechnical Engineering at Lucerne University of Applied Sciences and Arts, School of Engineering and Architecture. Dr Arnold studied Civil Engineering at ETH Zurich and received his PhD from ETH Zurich under supervision of Prof Sarah M. Springman and Prof Jan Laue. He has been working in the Higher Education sector in Switzerland since 2011. He is leading and delivering several geotechnical-related modules at HSLU such as soil mechanics and geotechnical engineering. He also supervises students in their project works as well as in their BSc- and MSc theses. He was involved in several industrial projects on the design of retaining structures, excavations, piled foundations, shallow foundations and anchored structures in slopes. He has also been managing industrial and scientific joint research projects using centrifuge model testing.

Hansjörg Vogt, Lucerne University of Applied Sciences and Arts (Switzerland)

Hansjörg Vogt is a highly experienced civil engineer with an extensive academic and professional background. He holds a degree in Civil Engineering from ETH Zurich and a Master of Engineering from Rensselaer Polytechnic Institute in Troy, NY. Over the course of his career, he has held numerous key project engineering roles and is currently the Managing Director of his own consulting firm in Liechtenstein. His expertise is particularly focused on geotechnics and earthquake engineering for complex projects. With over 30 years of successful practice, he has also taught Geotechnical Engineering at the University of Applied Sciences of the Grisons and Lucerne University of Applied Sciences and Arts. He presently serves as Program Leader for the CAS Foundation Engineering at HSLU.

Project-based learning on the design of retaining walls for geotechnical and civil engineering students

O. Jenck^{1,2} & D. Ricotier¹

¹ Institut National Polytechnique de Grenoble, Université Grenoble Alpes, Grenoble, France

² 3SR, Université Grenoble Alpes, Grenoble INP, CNRS, Grenoble, France

orianne.jenck@univ-grenoble-alpes.fr, damien.ricotier@univ-grenoble-alpes.fr

ABSTRACT: This communication details a teaching method of the retaining wall design for future geotechnical and civil engineers, through the implementation of a project-based learning. The case of an inverted T-shaped (or cantilever) reinforced concrete wall is chosen, as it integrates two disciplines that were previously taught separately: geotechnical engineering and structural mechanics. This also enables the students to grasp the multidisciplinary features of a real situation. The project involves the design of a wall to satisfy external and internal wall stabilities following the Eurocodes (7 and 2), without resorting to dedicated software, with a view to assimilating the concepts. Additionally, a small-scale model is considered during the project, that highlights the different modes of wall failure. This paper presents the project, its implementation and assessment.

Keywords: *Project-based learning, active learning, retaining walls, reinforced concrete structures, geotechnical engineering.*

1 Introduction

In France, as elsewhere in the world, alternative teaching methods are on the increase, in particular active learning through project-based learning (APP), which emerged some fifty years ago in Canada. The aim of this form of teaching is to generate learning by carrying out a concrete study, here on a professionally oriented project. This learning process is said to increase and improve the students' commitment, and to ensure a sustainable learning acquisition. Another benefit of the method is the development of cross-disciplinary skills such as project management and collaborative working. However, the disadvantages are that students would have a less rigorous understanding of the fundamentals and that problems can be generated between group members (Airey, 2008), even if it also means learning how to manage conflict. In addition, this type of teaching is time-consuming. These projects can be set up to generate learning of fundamental scientific elements (Ricotier et al., 2017), or to acquire advanced knowledge and expertise (Delage et al., 2006; Gavin, 2011).

In the Geotechnical and Civil Engineering Department of Polytech Grenoble (Engineering School of National Polytechnique Institute of Grenoble - Grenoble Alps University) such projects have been established for several disciplines. This communication presents a project devoted to the learning of the design of retaining walls. The design of a reinforced concrete cantilever wall enables geotechnical engineering and structural mechanics approaches to be tackled in a single project, by checking the external stability of the wall, which is of geotechnical origin, and the internal stability, which is a matter of structural mechanics. The project set up here requires prior knowledge of soil mechanics and the design of reinforced concrete structures, and aims to train students in the design of retaining walls mid-way through their engineering training. Moreover, in order to give students a clear understanding of the possible modes of failure of this type of structure, which are the basis of the design, they are offered a study using an analogue scale model.

2 Project based learning (PBL) principles

PBL is based on three pedagogical principles:

- i) Motivation for learning (Saint-Onge, 2008), by confronting the student with a problem similar to those they will encounter in their future professional life,
- ii) Collaborative work in small groups, supervised by a tutor,
- iii) The generation of generic skills linked to problem solving (rational and analytical approach to a situation, research, structuring and integration of different resources and information to solve the problem), group work and individual work.

During group work sessions, the tutor is not/no longer a teacher but a 'facilitator'. Its role is to lead group discussions, ask questions, facilitate and, if necessary, provide a diagnosis to help each student acquire the knowledge and develop the skills they are aiming for. Question-and-answer sessions can be planned, during which the tutor resumes his teaching role and provides answers to the students' questions, in the form of a course in front of the entire student body.

3 Objectives of the project

3.1 Design of a retaining wall

The aim of the project is for students to acquire skills in designing gravity walls in general, and cantilever walls in particular. The studied case is rather simplistic, as the purpose is to understand the mechanical behaviour, to focus on the general design methodology (in particular, to be able to tackle each possible failure mode, with appropriate sets of partial factors) within a normative framework.

The project consists of designing an inverted T-wall made of reinforced concrete, retaining a homogenous soil mass, in accordance with Eurocode standards (French application standards for the Eurocodes). The case study is depicted on Figure 1. The height and thickness of the wall are given as input data due to the allocated time constraint.

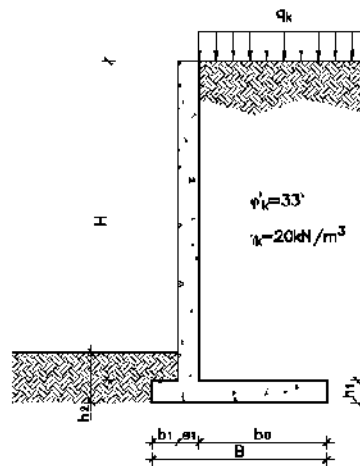


Figure 1. Vertical schematic cross section of the studied wall.

The students are asked to i) determine the geometry of the wall (width B of the footing) in order to ensure the external stability of the structure; ii) determine the reinforcement required to ensure the internal stability of the structure; both parts in accordance with the national application standards of the Eurocodes.

This project has been implemented since 2017, as detailed by Jenck & Ricotier (2019). While the main objectives remain unchanged, the input data change every year, forcing the students to redo the project in case they borrow the outcome from the preceding cohort. For instance, the value of the height of the wall, the soil friction angle, the value of the surface surcharge, the angle of the slope of the retained soil, the case of a cast-in-place or prefabricated walls (which changes the friction under the base of the structure), etc. can be easily varied. This may lead to different dimensional situations and different sets

of partial factors. In addition, we insist on understanding and applying the methodology, which students still find difficult to plagiarise from one year to the next. Besides, at the end of the project, the students are required to complete an individual exam (see Section 5). Moreover, a very recent novelty is the implementation of a small-scale model to highlight the mechanisms (see Section 4.4), that also requires the students to do more than simply apply equations (that dedicated program/software can automatically do).

3.2 Acquisition of cross-disciplinary engineering skills

The skills to be acquired by students during this project may relate to the skills reference framework of the 'Commission des Titres d'Ingénieurs', which is the French body responsible for issuing the accreditation of curriculum leading to the award of the engineering degree. The framework contains i) scientific and technical aspects, and ii) personal, organisational and cultural dimensions. For each item, several levels can be reached. For level 1, the skill is not acquired. Acquisition of the skill can be satisfactory from level 2 or 3 upwards.

Concerning the scientific and technical aspects, the skills are:

- Ability to choose and implement tools and methods (level 1 corresponds to “unable”, level 4 is “ability to choose, adapt and implement tools and methods with justification of the choices”),
- Ability to identify, analyse needs and constraints, and formalise specifications,
- Ability to present, write and document the solution,
- Ability to find relevant information and to exploit it.

Concerning personal, organisational and cultural dimensions, the skills are:

- Ability to communicate/interact with different interlocutors,
- Ability to integrate into professional life, into an organisation,
- Ability to lead, develop a team, commitment and leadership,
- Ability to take on responsibilities, initiatives, make choices,
- Ability to know yourself, self-evaluation, define your career.

All these items must of course be adapted and put into perspective with regard to the present project. Nevertheless, this part prepares students for the assessments of their future placements and projects, which are now increasingly based on ‘skills-based assessment’.

4 Practical implementation of the project

4.1 Students involved and prerequisites

This project is aimed at students in their 2nd year of engineering school (M1 equivalent), in the Geotechnical and Civil Engineering department. The students already have a strong knowledge of soil mechanics, strength of materials, calculation of reinforced concrete structures. They have previously designed structures and applied the principles of the Eurocodes, in particular for foundations (external stability) and reinforced concrete structures such as beams and columns (internal stability). This PBL is offered to students at the end of semester 7, during which they already have attended classes and tutorials in the two subjects “Reinforced Concrete” and “Retaining Structures”. However, they haven’t dealt yet with the design of gravity walls, nor the specific case of inverted T-walls, but they were taught the basics they need to understand the design concepts: the principle of calculation of reinforcement for ‘classic’ structures, the concepts of earth pressure and the design of embedded retaining walls. Additionally, the scale model has already been used in lessons to illustrate how embedded retaining walls work.

4.2 General organization

The total duration of the project is three working days (8.45 am to 4 or 5 pm). The three sessions were initially consecutive, but following students’ feedback, it is now planned one day a week during three consecutive weeks. The students are in groups of 5 or 6, tutored by a teacher. The two teachers each tutor several groups (3 or 4). All the groups deal with the same project.

A project day always begins with a group session, then alternates sessions of individual work, group work, includes a question-and-answer session at the end of the morning, and a feedback session at the end of the day. The feedback session consists in writing a poster followed by an oral presentation by a group chosen by lottery, then questions and remarks from the teachers, and a discussion. More details on the daily organization is given by Jenck & Ricotier (2019).

The group assessment is based on the poster and presentation, while an individual assessment is scheduled at the end of the project, in the form of a multiple-choice questionnaire (see Section 5).

4.3 Project content and guidance

Students are guided by a booklet that includes the project statement and objectives for each day, including an assessment grid and references to useful books (Ricotier, 2021), courses and standards. Useful standards are provided on the numerical working platform (French standards AFNOR, 2005 and AFNOR, 2014, relative to Eurocode 2 and 7 respectively).

An English translation of the assessment rubric items relative to the first day, more specifically devoted to the geotechnical engineering part, is given on Table 1. The students have this rubric list in their booklet and this should guide them in their progress throughout the session, and so they know what is expected in their report at the end of the day, as well as the technical skills they need to acquire.

Table 1. Items of session 1 assessment grid

Disciplinary objectives	Mark and comments
The various modes of failure of this type of structure are correctly and succinctly presented.	
The calculation model(s) for verifying the external stability of the wall is (are) correctly presented and illustrated with clear, captioned figure(s).	
The verification of the sliding stability is carried out in accordance with the standard, with the relevant parameters explained and analysed qualitatively (heel, various angles, earth coefficients, partial factors, characteristic and design values of the actions).	
The verification of the eccentricity at serviceability limit state (SLS) is made and understood: the calculation model is presented on a clear figure, the article of the standard is quoted, the partial factors utilized are correct and justified, the criterion is verified.	
The verification of the eccentricity at ultimate limit state (ULS) is made and understood: same items as for SLS.	
A solver is used correctly and gives an exact value for the needed heel width b_0 for each of the envisaged failure modes.	
For the final value of the footing width, a table and/or a figure with the actions and their factors, for each failure mode, are given, as well as the results of the regulatory checks.	
The analyses of the failure modes observed on the small-scale model are relevant.	
Quality of visuals	
The language is used rigorously (equations, words, units), spelling and grammar are correct.	
The poster presentation is structured and original.	
Structure of the oral presentation	
The presentation is structured (problem, unknowns, method).	
Quality of oral presentation	
The student masters what she/he is presenting, the visual information is reformulated, additional information is given.	
Oral expression	
The language is correct, the voice volume, the pronunciation and the flow are appropriate, the visual contact is maintained with the public.	
Positive aspects and areas for improvement	

As explained on Table 1, the first session is devoted to the geotechnical engineering part, as the students have to consider the wall external stability. The sessions 2 and 3 are focused on the reinforced concrete wall design regarding the internal stability (not detailed more in this communication). Session 2 is focused on the vertical wall slab, and session 3 covers the internal design of the footing and the complete reinforcement plan for the wall. Geotechnical engineering input is then also needed for these sessions



Figure 3. Aluminum rods.



Figure 4. Natural slope of a rod assembly.

The photographs of Figure are given to the students with the task of analysing and discussing the failure modes of the two cases illustrated. The failure state is obtained from “initial” state after removing a few rods downstream of the wall. The scale-model is available to them to reproduce situations, for a clearer view of the kinematics of rupture. NB: for case 2, the heel and toe are deliberately reversed in order to bring out their respective roles. The students are also invited to model additional situations on their own initiative (for instance with a surface surcharge, either upstream or downstream, or with an upstream slope). They must then transcribe their analysis in their report, without any calculation.

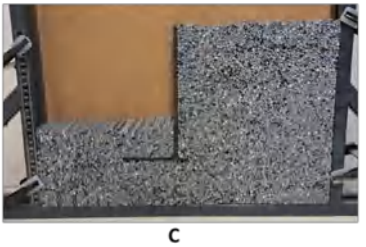
	Initial state	Failure state
Case n°1	 A	 B
Case n°2	 C	 D

Figure 5. Proposed case studies for the wall external stability using the small-scale model.

This small-scale model implementing the soil analogue is also used during the dedicated lecture as a demonstrator for the embedded walls and their failure modes, in particular to distinguish the modes of failure for cases that are simply embedded or with a support level. A simple steel plate is then used. The model is also used as a demonstrator for geotextile reinforced retaining wall (using fabric strips for the geotextile).

5 Outcome assessment

The students' assessment has evolved during the years, adapting to feedback from experience. At present, the assessment is carried out in the form of the evaluation of the poster of each of the three sessions, using the assessment grid (example in Table 1) of the evaluation of oral presentation if applicable, and of an individual assessment by a questionnaire, at the end of the third and last project days (25 to 30 minutes for the geotechnical engineering part).

5.1 Group assessment

At the end of each session (day), a group selected at random presents its work for around ten minutes (methodology and results) in front of the whole classroom, with the poster projected on a large screen at background. Afterwards, a question-discussion session takes place, to clarify certain points and to broaden the scope of the work, so that learning is not limited to the simplified case dealt within this project. We also look at optimisation levers and existing alternative solutions, with a view to taking into account the environmental impact of the structures and the cost study, even if these points are not detailed in the work requested. During the discussion, students also comment on their acquisition of cross-disciplinary skills through this project, as described in Section 3.2.

5.2 Individual assessment

The individual assessment takes place at the end of the third session through a questionnaire. The questionnaire has multiple-choice questions (MCQ), answers requested in the form of a numerical result to be coded on the copy, and open questions. Each statement has a different set of numerical input data, leading to a different numerical result for each (the aim is to avoid cheating).

The example below dates back a few years and concerns the geotechnical engineering part. The duration was 25 min.

For calculation questions, the numerical result has to be coded on the answer sheet. For MCQ, there can be several correct answers (and there is always at least one). Points are deducted for ticking the wrong boxes twice or more. An automated correction system is used, except for open questions, which must be marked manually by the examiner before scanning (with possibly negative points for an obvious serious error).

As documents are not permitted (calculator only), an appendix is provided, setting out the main equations to be verified for sliding and load eccentricity at the wall base, without additional explanation, as these equations were used during session 1. The parts in italics are those written on the statement.

Part 1

The gravity wall depicted on Figure 6 is considered (cast in place concrete at the wall base). The characteristic value of the unit weight of the material constituting the wall is an input data and is not identical for all statements (varies between 20 and 25 kN/m³ in steps of 0.5 kN/m³).

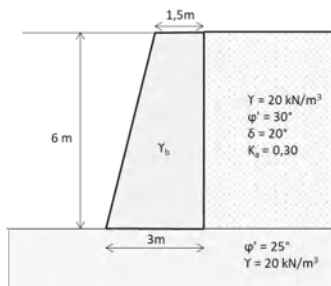


Figure 6. Gravity wall to consider for the evaluation (part 1)

The sliding stability is first considered (ultimate limit state).

Question 1: Determine the design value of the horizontal load on the wall, in kN/m (give the result to the nearest kN/m).

Question 2: Determine the value of the total horizontal resistance $R_{th,d}$ in kN/m (give the result to the nearest kN/m).

Question 3: Calculate the ratio $\frac{R_{th,d}}{H_d}$ (give the result to an accuracy of 1/10).

Question 4: To check slip stability, the ratio $\frac{R_{th,d}}{H_d}$.

A - must be equal to 1

B - must be greater than or equal to 1.35

C - must be less than 1

D - must be greater than or equal to 1

E - none of the above is correct.

Question 5

- A - Stability against sliding is assured.
- B - Stability against sliding is not assured.
- C - The data provided do not allow a conclusion to be drawn on sliding stability.

The verification of the eccentricity of the resultant under the base of the structure is now considered.

Question 6. For this verification:

- A - The weight of the wall is an unfavourable permanent action.
- B - The soil active earth pressure on the wall is an unfavourable variable action.
- C - The weight of the wall is a favourable permanent action.
- D - The soil active earth pressure is a favourable permanent action.
- E - None of the above is correct.

Question 7: (e is the load eccentricity, definition given in the appendix, with the equations).

- A - For SLS verification, e must be greater than 0.75 m
- B - For SLS verification, e must be less than 0.75 m
- C - For ULS verification, e must be greater than 0.06 m
- D - For ULS verification, e must be less than 1.40 m
- E - None of the above is correct.

Question 8: Indicate the design value of the vertical load transmitted by the wall to be considered in determining the eccentricity at the ULS (give the result to the nearest kN/m).

Question 9: Indicate, in m, the value of the eccentricity obtained at the ULS (to the nearest cm).

Question 10: Indicate, in m, the design value of the vertical load transmitted by the structure to be considered for determining the eccentricity at the SLS (give the result to the nearest kN/m).

Question 11: Indicate, in m, the value of the eccentricity obtained at the SLS (to the nearest cm)

Question 12

- A - Eccentricity is checked at the ULS and at the SLS.
- B - Eccentricity is checked at ULS but not at SLS.
- C - Eccentricity is checked at ULS but not at SLS.
- D - The eccentricity is checked neither at ULS nor at SLS.
- E - The data provided do not allow a conclusion to be drawn on the verification of eccentricity.

Question 13: In the box below, draw a diagram of the wall showing the eccentricity e, and the actions H_d and V_d , at the ULS. An insert is then provided in the answer sheet.

Part 2

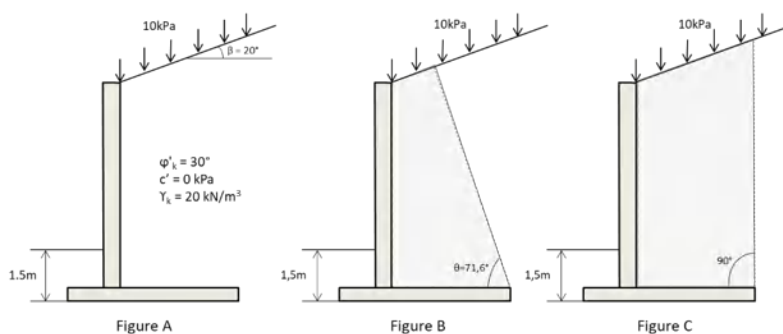


Figure 7. Cantilever wall to consider for the evaluation (part 2).

Question 14: For the verification of the external stability of the wall depicted on Figure 7, the monolithic block to be considered at the rear of the wall:

- A - is the one shown in figure B, and the one shown in figure C cannot be considered.
- B - is the one shown in figure C, and the one shown in figure B cannot be considered.
- C - is either that shown in figure B or that shown in figure C.
- D - depends on the mobilisable friction under the base of the structure.

Question 15: To check the internal stability of the wall:

A - The monolithic block shown in Figure B or Figure C (your choice) is considered to determine the actions on the wall vertical slab.

B - The monolithic block in figure B (but not in figure C) is considered to determine the actions on the wall vertical slab.

C - The monolithic block of figure C (but not of figure B) is considered to determine the actions on the wall vertical slab.

D - The monolithic block from figure B or figure C (as chosen) is considered to determine the actions on the heel.

The assessment therefore includes both numeracy and comprehension questions, since numeracy alone is not enough to assess this. In spite of the calculations and the questions of comprehension that seem easy at first sight, the average mark was 7.9/20 (over 40 students) for the assessment example given above (in 2024), which is clearly poor and disappointing. The average mark of the structural engineering part of the same session was 9.2/20, which is not completely satisfactory either. The possible reasons are that it was probably too long (especially if the preparation wasn't serious enough), that the students were tired after a full day of project work, that they didn't seriously rework the concepts seen in session 1, that the marking (with negative points and numerical values to be coded) was too severe. From the students' point of view, the main reason would be the time allocated, which is too short. Another reason is that there is not enough time to learn and understand the geotechnical part, with only one day out of the three of the project (even though the geotechnical aspects are necessary for the 'structure' parts). In the future, serious consideration is being given to increasing the duration of the geotechnical part (with the same objectives) and reducing the duration allocated to the 'structure' part (by removing or lightening the requirements, in particular concerning the details of the constructive provisions for the reinforcement of the wall, which appears to be less important at this stage of curriculum than understanding the fundamental concepts). Unfortunately, the total duration of the project cannot be increased (because of the very tight teaching schedule). Meanwhile, the same required level was subsequently maintained for this assessment (but subject has a different wording and numerical application every year). The average increases slightly each year (similar assessment), as students are warned of the difficulty of this assessment and prepare for it more seriously.

The evaluation has not yet taken place this year, but it is hoped that the more in-depth concepts expected from the analysis of the reduced model will make up for certain shortcomings. If this is not the case, the assessment may be modified for next year.

This poor score is weighted against the collective score, which is generally much better, and the overall mark for the 'retaining structures' module takes into account the assessment of other parts of the programme, with assessment methods other than MCQs.

Additional examples of multiple-choice questionnaire (in French) can be provided to readers on demand.

6 Conclusions

This paper presents an alternative learning method to the traditional lecture and exercise scheme, focusing on the design of a (cantilever) retaining wall for future geotechnical and civil engineers.

Project-based learning allows students to take an active role in their training, thereby increasing their motivation and involvement, which certainly leads to a more secure and lasting acquisition of their knowledge (even if the results of the individual assessment of this project are mixed).

This project also highlights the link between geotechnical engineering and structural design (the stresses to be taken into account for the internal design of the structure are derived from a relevant geotechnical model), whereas these two disciplines were previously taught separately.

Additionally, a small-scale model is considered during the project, which highlights the different modes of wall failure. The latter contributes to the objective of making the students understand the different geotechnical models that have to be considered depending on the mode of failure envisaged, rather than mindlessly applying formulas that software or AI could do for them.

During the discussion with the students at the end of their oral presentation, we get them to think about alternative retaining structures to those made of concrete as mainly considered in this project, or optimisation levers. The need to consider the environmental impact of the structures when designing them is also mentioned. Unfortunately, this aspect is not dealt with in greater depth in this project, which

would otherwise be too ambitious for the time available, but we are currently thinking about a way of integrating it nonetheless. These concepts are covered in other modules of the curriculum. The cost study is not addressed in this project either, which is limited solely to the technical dimensioning aspect.

To conclude, this type of alternative teaching requires a great deal of commitment on the part of the teaching staff (setting up and running the course), but provides a certain satisfaction in seeing the students more involved in their training and in an effective learning situation, while strengthening the cohesion of the teaching team.

Acknowledgements

The teachers acknowledge former student Thibaud Exertier (graduated in 2024) for building the frame of the small-scale model, under the guidance of our colleague Christophe Dano; and the Technical University Institute of Grenoble for the donation of a batch of aluminium rods (soil analogue). The authors are also grateful to the reviewers for their constructive comments.

References

- AFNOR (2005). Eurocode 2 - Calcul des structures en béton - Partie 1-1 : Règles générales et règles pour les bâtiments. Norme Française NF EN 1992-1-1 (*Eurocode 2 - Design of concrete structures - Part 1-1: General rules and rules for buildings. French Standard NF EN 1992-1-1*).
- AFNOR (2014). Justification des ouvrages géotechniques. Normes d'application nationale de l'Eurocode 7. Ouvrages de soutènement — Murs. Norme Française NF P 94-281 (*Justification of geotechnical structures. Standards for the national application of Eurocode 7. Retaining structures - Walls. French standard NF P 94-281*). 105p
- Airey, D.W. (2008). A project based approach to teaching Geotechnical Engineering. Education and Training in Geo-Engineering Sciences. Taylor and Francis Group, 357-362.
- Biarez, J. (1962). Contribution à l'étude des propriétés mécaniques des sols et des matériaux pulvérulents. Thèse de Docteur ès Sciences (*Contribution to the study of the mechanical properties of soils and powdered materials. Doctor of Science thesis*). Université de Grenoble, France. In French.
- Delage, P., De Gennaro, V., Bernhardt, V., Simon, B. (2006). Un enseignement par projet de la géotechnique (*Project oriented geotechnical teaching*), Revue Française de Géotechnique 115, 37-42. In French.
- Gavin, K. (2011). Case study of a project-based learning course in civil engineering design. European Journal of Engineering Education 36(6), 547-558.
- Jenck, O., Ricotier, D. (2019). Apprentissage par projet du dimensionnement des murs de soutènement en béton armé pour des élèves-ingénieurs en Géotechnique et Génie Civil (*Project-based learning on the design of reinforced concrete retaining walls for geotechnical and civil engineering students*). XVII European Conference on Soil Mechanics and Geotechnical Engineering, Reykjavík, Iceland. In French.
- Ricotier, D., Jenck, O., Dias, D., Oxarango, L. (2017). Apprentissage par projet multidisciplinaire pour les élèves-ingénieurs en géotechnique et génie civil, afin d'acquérir des notions fondamentales (*Multidisciplinary project-based learning for geotechnical and civil engineering students, to acquire fundamental concepts*). 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul, South Korea. In French.
- Ricotier, D. (2021). Dimensionnement des structures en béton selon l'Eurocode 2 (*Designing concrete structures according to Eurocode 2*), 2nd ed.. Le Moniteur, Paris, France. In French.
- Saint-Onge, M. (2008). Moi j'enseigne, mais eux apprennent-ils ? (*I teach, but do they learn?*). Chronique sociale, 123p. ISBN : 978-2-85008-721-9. In French.
- Schneebeli, G. (1956). Une analogie mécanique pour les terres sans cohésion (*A mechanical analogy for cohesionless soil*). Comptes rendus des séances de l'Académie des Sciences. Tome 243. Paris 1956. In French.

Authors' bios

Orianne Jenck, National Polytechnique Institute of Grenoble, Grenoble Alpes University (France)

Dr. Orianne Jenck is an associate professor at Grenoble Alpes University. She holds her civil engineering degrees (Engineer and PhD) from Institut National des Sciences Appliquées (INSA) of Lyon, in France. She is teaching at Polytech Grenoble, an engineering school, on the Geotechnical and Civil Engineering department, in the fields of soil mechanics and geotechnical structures, and she was responsible for the work-study contract option for ten years. She is a researcher in the 3SR laboratory in Grenoble, in the team "Geomechanics". Her main area of research focuses on the study of the mechanical behaviour of geotechnical structures that involve strong soil-structure interactions and submitted to complex solicitations, for which she is developing experimental and numerical approaches. She is a member of the scientific and technical committee of the CFMS (French chapter of ISSMGE), and she is a member of ISSMGE TC104 Physical Modelling in Geotechnics and TC306 Geoengineering Education.

Damien Ricotier, National Polytechnique Institute of Grenoble, Grenoble Alpes University (France)

Damien Ricotier is associate professor of civil engineering at Grenoble Alpes University. He holds an engineering degree in civil engineering and is an alumnus of the Ecole Normale Supérieure de Cachan (ENS). He has been teaching structural mechanics and reinforced concrete for twenty years at the Polytech Grenoble engineering school, in the Geotechnics and Civil Engineering department. He was in charge of the department between 2017 and 2023. He has been teaching reinforced concrete for Grenoble INP's continuing education program for the past 5 years. He is also the author of the book "Dimensionnement des structures en béton armé selon l'Eurocode 2" published in 2021, 680 pages, by Éditions du Moniteur.

Using educational escape rooms in soil mechanics laboratory courses

K. Kluge¹, C. Budach² & A. Kirsch³

¹University of Applied Sciences Mainz, Germany
katharina.kluge@hs-mainz.de

²University of Applied Sciences Köln, Germany
christoph.budach@th-koeln.de

³University of Applied Sciences Aachen, Germany
kirsch@fh-aachen.de

ABSTRACT: This article presents three educational escape rooms designed by the authors, which were implemented in soil mechanics laboratory courses at their universities. Initially, an overview is provided of how escape rooms have evolved within the entertainment industry, which types of tasks and structures exist and how they reached the educational sector. Educational escape rooms (eduscapes) confront learners with subject-specific content that they have to solve in a playful way. The article reports on the results of a survey on laboratory courses conducted among German-speaking geotechnics professors in Germany, Switzerland and Austria. Further, eduscapes developed by the authors are presented. The framework conditions, structure, and content of the developed eduscapes are outlined and two examples of puzzles are presented.

Keywords: *escape room, eduscapes, soil mechanics laboratory, laboratory tests, sieve analysis, active learning*

1 Escape rooms as an interactive experience: development and structure

1.1 Development of escape rooms

Escape rooms have become a popular form of interactive entertainment in recent years. The first well-documented escape room was opened in July 2007 in Kyoto, Japan, by the company SCRAP (see Nicholson, 2015). Between 2012 and 2013, the concept spread rapidly, first in Asia, then in Europe, and finally in Australia, Canada and the United States. Nicholson (2015) traces the origins of escape rooms back to various predecessor games, for example live-action role-playing games, digital point-and-click adventures, treasure or scavenger hunts, interactive theatre or adventure and game shows.

Nicholson (2015) describes escape rooms as team-based adventure games in which participants must solve challenging tasks, so-called puzzles, within a given time frame and under time pressure. The objective is to escape from the room, in which they are locked, by solving the puzzles and, thus, finally winning the game. If the escape rooms are well designed, they offer an immersive experience. Wiemker et al. (2015) compare this experience to immersion into a good book or film.

1.2 Construction of escape rooms

Escape rooms can be designed as games that participants play physically, digitally or in hybrid variants. While physical escape rooms predominated in early years, digital ones have increasingly emerged since

2020, mostly as a reaction to the COVID-19 pandemic, see Buchner (2022). An escape room is made up of various puzzles which can be divided into two categories according to Wiemker et al. (2015):

1. Mental puzzles are tasks in which the participants use their cognitive abilities to find the solution. This may involve calculations, deciphering codes or recognising patterns, for example. Connections must be drawn, relationships understood and logical dependencies recognised.
2. Physical puzzles are tasks in which the participants are physically active. Challenges such as crossing a laser grid or searching for certain objects in the room lead to the solution of a task.

In order to solve the puzzles, creativity, critical thinking, collaboration and a change of perspective are required for both types of puzzles. Hörsch et al. (2023) also emphasise the importance of good communication between the participants. According to Nicholson (2015), teamwork, delegation, attention to detail and thinking 'outside the box' are crucial for success in escape rooms. Thus, in addition to mental and physical challenges, soft skills also play an important role in dealing with escape rooms.

The mental and physical puzzles of an escape room are linked by an 'over-all'-puzzle, the so-called meta-puzzle. The path from the start to the finish, i.e. the structure of the escape room, can be organised differently:

1. Linear path: The puzzles are to be solved in a fixed order, i.e. solving one puzzle leads to the next. Therefore, the design is relatively easy as each individual puzzle only has to be linked to another. Also for participants, the structure is easy to understand. However, problems arise for the participants if they cannot solve a certain puzzle and get stuck, see Geissler (2024).
2. Open path: Here, the puzzles can be worked on in any order. However, as within the linear structure, all puzzles must be completed in order to solve the meta-puzzle. This structure is more complex for both the creators and the participants. During the design phase, several puzzles must be interlinked and sufficient information must be provided for each puzzle. When working on a puzzle, the path from one puzzle to the next is not predetermined and may therefore be more challenging.
3. Multilinear path: Here, there are several linear puzzles that can be worked on in parallel. This allows the tasks to be completed more flexibly, but the start of a puzzle line may be more difficult to find. Nevertheless, all puzzle pieces must be solved to successfully complete the escape room.

Regardless of the structure, it is important that a game master is on hand to support the participants and to provide hints and assistance if necessary. According to Buchner (2022), audio and video recordings, written instructions or personal hints can provide this support. Also very important is a briefing at the beginning of the escape room and a debriefing at the end to release the participants back into the real world.

2 Combining learning and playing in educational escape rooms

2.1 Development of educational escape rooms

The growing popularity of escape rooms in the entertainment sector has led to the development of educational escape rooms (eduscapes) used in schools and universities. In studies by Fotaris & Mastoras (2019) and Veldkamp et al. (2020), the structure, organisation and characteristics of numerous eduscapes are examined. According to Fotaris & Mastoras (2019), the first publication on an eduscape dates back to 2009 - from 2017 onwards, the number of publications on eduscapes increased dramatically. Veldkamp et al. (2020) emphasise that these eduscapes were created "bottom-up" by dedicated teachers who adapted their experiences from recreational escape rooms and developed eduscapes for the classroom.

2.2 Design of educational escape rooms

While escape rooms in the entertainment industry are aimed at a broad audience, eduscapes are designed for specific learning groups and pursue clearly defined learning objectives. Fotaris & Mastoras (2019) define eduscapes as a didactic method that encourages learners to engage in playful, collaborative activities in order to acquire knowledge or skills in a specific subject. The aim is to achieve specific learning objectives within a limited time frame by solving puzzles. Unlike escape rooms in the

entertainment industry, eduscapes are often not about finding a way out of a room and successfully completing the game, but about opening a combination lock on a box and finding a reward inside. Even if the story behind the eduscapes is often not as thrilling as the ones from the entertainment industry, the tasks should be embedded in a story that motivates people to solve the tasks. Playing and learning are therefore combined in the eduscape and, according to Kerres (2018), the concept of “game-based learning” creates a training environment that enables the targeted acquisition of knowledge and skills.

Eduscapes appeal to learners on many levels: in addition to subject-specific knowledge, problem-solving skills and critical thinking, learners are required to use soft skills such as teamwork, communication, creativity and commitment when solving the tasks. Thanks to their versatility, eduscapes enable problem-based learning that quickly creates learning success, is fun and has a strong motivational effect. Explorative learning, in which, according to Kerres (2018), learning is not understood as a linear process but as a versatile and motivating activity, is promoted in eduscapes by requiring learners to try out different ways to solve the puzzles and gain new experiences in the process. However, it is important for learning success of participants that all learners are ultimately able to complete the tasks and, thus, achieve the learning objectives. Therefore, also in eduscapes, a game master should always be present to give continuous feedback as well as hints if problems arise. Otherwise, the experience will lead to frustration and demotivation.

2.3 Challenges of educational escape rooms

In their research, Fotaris & Mastoras (2019) and Veldkamp et al. (2020) identify several challenges that need to be overcome when developing eduscapes. For example, it is essential that the tasks of the escape room match the content of the respective course and the learning objectives that have been formulated for the escape room. The tasks must neither be too easy, as they would otherwise cause boredom, nor too difficult, as this would lead to frustration. In addition, the puzzles must be achievable within the specified time frame. As most eduscapes are held in classrooms, seminar rooms or laboratories, it is also important that the eduscapes can be set up and dismantled quickly and easily. Moreover, they must be designed in such a way that many people can participate simultaneously or consecutively, as student groups are usually larger than groups in leisure escape rooms. In order to allow everyone to participate, group sizes of three to six people are suitable, which is very challenging for large courses in terms of organisation. According to Veldkamp et al. (2020), the playing time of eduscapes is usually between 20 and 120 minutes, with an average of 60 minutes. Financial resources can also be limited and, thus, represent limiting factors. All of these points require a great deal of time for the design of eduscapes, but also for their implementation and support.

3 Development of own educational escape rooms

3.1 General information

This section explains the background and learning objectives for three different eduscapes for soil mechanics laboratory courses, which were designed independently of each other at the Universities of Applied Sciences of Mainz, Köln and Aachen, Germany. The overall concept was first presented in the Geotechnics Network for Innovations in Teaching (GeNIaL), which the authors founded in 2022 and which gives geotechnical professors all over Germany, Austria and Switzerland space to regularly meet and discuss teaching topics.

On the one hand, the eduscapes were created to liven up the standard laboratory classes with playful accents and to provide variety. On the other hand, the eduscapes are intended to help students gain a more profound understanding of the laboratory tests: instead of working on one laboratory test after the other, they have to work on several laboratory tests simultaneously in the eduscape. Moreover, they need to decide for themselves which laboratory test to carry out in order to determine certain characteristic values for the eduscape puzzles.

3.2 A survey of German-speaking geotechnical engineering chairs

The authors attach great importance to their aim that didactic material can also be used by other universities. In order to ensure relevance and to meet the requirements of laboratory practice, the laboratory tests addressed in an eduscape should reflect what is covered by the laboratory courses at

most universities. Furthermore, the authors wanted to find out in which parts of the degree programs laboratory courses are carried out at other universities, and whether escape rooms have already been used in the field of soil mechanics courses at other universities or not.

With these goals in mind, under the supervision of the first author, Wenz (2024) invited 92 professors for geotechnical engineering from universities in Germany, Switzerland and Austria to take part in a survey as part of his bachelor's thesis. This survey of five questions was completed by 39 people ($\approx 42\%$) in the summer of 2024. The main results are presented below, with the percentages referring to the 39 people who took part in the survey, see Wenz (2024).

Question 1: Do your undergraduate Bachelor's students carry out laboratory tests independently or largely independently as part of a laboratory course?

This question was affirmed by 28 people ($\approx 72\%$) while 11 people ($\approx 28\%$) negated this question.

Question 2: Please answer the following question if you answered "Yes" to the last question. Which laboratory tests are carried out at your college or university as part of a soil mechanics laboratory course in the Bachelor's undergraduate program?

To answer this question, 18 laboratory tests were specified for multiple selection. The requested laboratory tests and the result for this question are displayed in Figure 1. The six tests that are covered most widely are marked in green. As can be seen, the sieve analysis and the test to determine the plastic limit were selected most frequently (27 times each). The determination of the liquid limit according to Casagrande, the Proctor test, the sedimentation analysis and the determination of the density for maximum and minimum compactness) are still carried out in more than half of the laboratory classes.

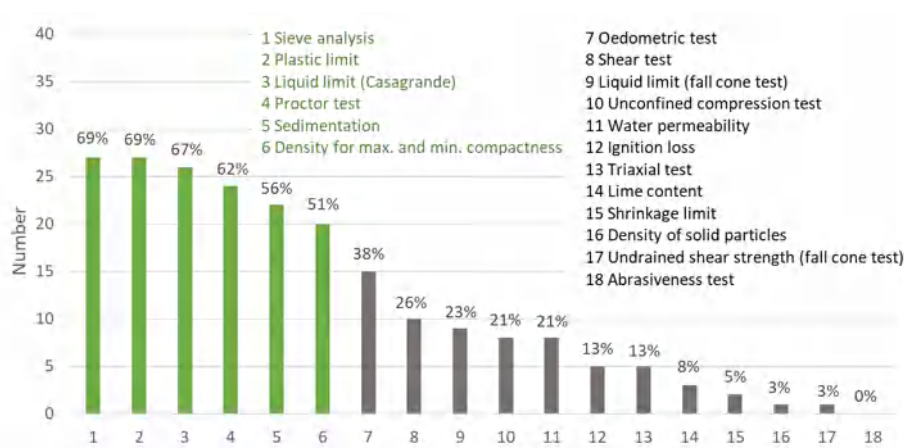


Figure 1. Number and proportion of laboratory tests carried out in laboratory courses. The tests that were mentioned by more than 50 % of the participants are marked in green.

Question 3: The previous questions were aimed at the Bachelor's undergraduate course. Are there any other soil mechanics laboratory courses at your university?

In response to this question, 19 persons ($\approx 50\%$) answered that soil mechanics laboratory courses are only carried out as part of the Bachelor's degree course. Laboratory courses in the Master's degree exist at 14 universities ($\approx 35\%$) and in the specialisation of the Bachelor courses at 7 universities ($\approx 20\%$).

Question 4: Have you ever designed and run an escape room yourself?

This question was answered with "No" by 37 of the 39 participants, with only 2 people stating that they had already designed and run an escape room themselves. It should be noted that the three authors of this article all took part in the survey and that the escape rooms at the Universities of Applied Sciences Köln and Aachen already existed at the time, whereas the escape room of University of Applied Sciences Mainz was still being designed. Hence, the two positive answers to this question came from two of the three authors themselves.

Question 5: Would you be interested in using an (already existing) geotechnical escape room for teaching purposes? If so, in what context?

While six people stated that they were not interested in an escape room, 33 people ($\approx 85\%$) would like to use one. There is particular interest in using an escape room in the undergraduate Bachelor's degree and, for example, as part of an open house day and also in using them in Master's degree and in specialisation courses, see Figure 2.

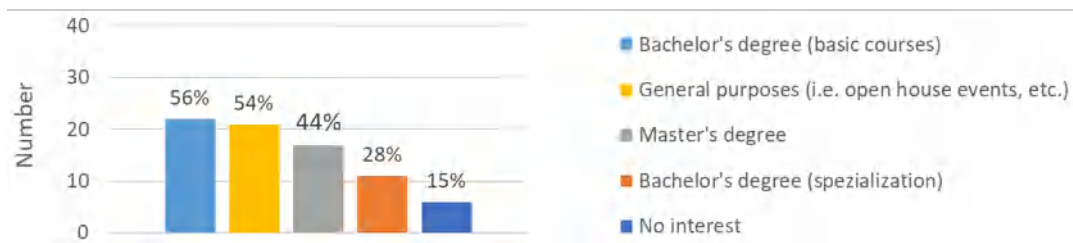


Figure 2. Interest in using an escape room in soil mechanics laboratory courses

3.3 Learning objectives

Unlike escape rooms in the entertainment industry, learning objectives are formulated for educational escape rooms. The authors consider the following learning objectives to be useful for an eduscape as part of a soil mechanics laboratory course in the Bachelor's degree program:

- Students are able to carry out soil mechanics laboratory tests independently.
- Students can evaluate measurement results from laboratory tests.
- Students can derive soil parameters from laboratory tests.
- Students can classify soil according to DIN 18196.
- Students can assess the suitability of soil for construction purposes according to DIN 18196.
- Students can extract information from a (hydro)geological map.
- Students can work in a team and communicate well with each other.
- Students can work together under time pressure.

The authors wanted to design their escape rooms for a maximum duration of 90 minutes. Therefore, it is not possible to allow enough time for students to carry out one or even several laboratory tests completely in order to achieve learning objective a). For this reason, for most of the laboratory tests included in the eduscape, measurement results are already provided. Students then only need to perform only one or two additional measurements or simply evaluate the test results. Hence, calculations, evaluations and classifications predominate in the escape rooms developed (learning objectives b) to f)).

Whereas students improve their technical and methodological skills by the tasks related to learning objectives a) to f), learning objectives g) and h) contribute to strengthening their social skills. By working on the partly practical and partly theoretical tasks in the escape room, students combine theory and practice, learning and gameplay. In some cases, the subject-specific puzzles were also supplemented with simple logic puzzles to offer the participants some variety. In order to ensure that the learning objectives are reached, it is important to provide feedback to the students. For example, this can be done as a debriefing of the students by the game master directly after completing the eduscape or in a separate session for all students in the classroom.

4 Examples of escape rooms and their implementation in laboratory courses

This section presents the eduscapes that the authors developed for their students in recent years. In order to differentiate they are named *Eduscape Mainz*, *Eduscape Köln* and *Eduscape Aachen*.

4.1 Eduscape Mainz

4.1.1 Target group and integration into the course

Eduscape Mainz was developed for the soil mechanics laboratory course that is mandatory for students of “Civil Engineering” and “International Civil Engineering” Bachelor's degree courses at University of Applied Sciences Mainz, Germany, in their 3rd semester. In the laboratory course, all students carry out several laboratory tests in groups of four over a period of around two months. To enable students to carry out the laboratory tests as independently as possible, all laboratory tests are discussed in detail in the lectures before. In addition, educational videos of 10 to 20 minutes each are available, which the authors of this article have produced in recent years and to which English subtitles will be added soon (see <https://www.youtube.com/@Geotechniksichtbarmachen>). An electronic test must be completed before conducting each laboratory test and another one must be processed and handed in afterwards. *Eduscape Mainz* is to form the conclusion of the laboratory course on a final compulsory laboratory date. So, students are once again confronted with all laboratory tests they have previously carried out.

4.1.2 Structure and content

Eduscape Mainz was designed with an open path structure in which the individual tasks can be solved independently of each other. Only one task requires a partial result from another task in order to complete it. Upon entering the lab, students find a sheet with the meta-puzzle on a laboratory table, which serves to determine the “solution code”. This solution code consists of three digits that are calculated from the results of the individual puzzles in *Eduscape Mainz*. The code can be used to open the lock of a box - opening the box marks the successful completion of the eduscape.

The sheet with the solution code does not explicitly state the laboratory tests that the students have to complete. It merely requires certain characteristic values and test results as numerical values with which the solution code is calculated by addition, subtraction, multiplication and division. The students must recognise which laboratory tests have to be conducted to obtain these values and must go to the locations of these tests in the laboratory. There they will find corresponding notes, test data sheets, aids and instructions.

At least the following six laboratory tests are covered in *Eduscape Mainz*, as these were the tests most frequently mentioned in the survey of German-speaking geotechnics departments presented in Section 0: Sieve analysis, plastic and liquid limits, Proctor test, sedimentation analysis, maximum and minimum dry density of granular soils. Tasks have also been developed for three further laboratory tests, which can optionally be integrated into *Eduscape Mainz*: oedometric test, shear test, unconfined compression test. Depending on how many tasks are integrated into *Eduscape Mainz*, a time of 60 minutes or a further 10 minutes per additional task is intended. The ideal number of people is considered to be four, as this ensures that everyone can take part in solving the puzzles.

4.1.3 Preparation of students and supervision in the laboratory

The students are prepared for *Eduscape Mainz* by completing their laboratory course in which they get to know all laboratory procedures in detail, conduct the tests and evaluate them. On the actual eduscape date they are allowed to use their collection of tables (including for example the plasticity diagram acc. to DIN 18196 (2023)) and a sheet with formulas – both aids are allowed for use in their exam, too.

In advance of *Eduscape Mainz*, the laboratory staff prepare the equipment, soil samples and tasks. The eduscape begins with a briefing in which the students are introduced to the rules of the game. The puzzles of *Eduscape Mainz* are to be solved independently. However, the game master, i.e. laboratory staff, is on hand to provide guidance if the students have too much difficulty solving a task. The aim is not to check how far the students get, but to enable them to solve all the tasks within the given time. *Eduscape Mainz* ends with a debriefing of the students by the game master, in which the results of the tasks are summarised and reflected upon, thus anchoring what the students have learned.

4.1.4 Results of student participation and feedback

Eduscape Mainz has so far been completed by only one group of students and revised again in response to their feedback. It will be used and evaluated in 2025 as part of the laboratory course.

4.2 Eduscape Köln

4.2.1 Target group and integration into the course

The course “Geotechnics I - Soil Mechanics” has to be attended in the 3rd semester of the “Civil Engineering” Bachelors’ degree at University of Applied Sciences Köln, Germany. As part of the course, various laboratory tests are demonstrated. To deepen their knowledge on field and laboratory tests, students can also watch educational videos produced in cooperation, see section 0. Due to the size of the cohort (approx.. 160 students start the “Civil Engineering” Bachelors’ degree each year), it is not possible that students carry out the laboratory tests on their own at the beginning of their studies. This can only be done in the following semesters in specialisation courses. *Eduscape Köln* takes place in the laboratory for “Geotechnics and Tunnel Construction” and is intended for students in order to reactivate the laboratory contents for their exam while having fun at the same time. The game is scheduled to last 60 minutes. It can be reduced to 45 minutes, but thus, the time pressure on the students is increased.

4.2.2 Structure and content

Eduscape Köln was developed as part of the “Roll-out, Empowerment, Design in Engineering Education” (REDiEE) project and *Eduscape Köln* is designed as an open path. The students complete *Eduscape Köln* in groups of 4 to 6 persons by solving the given meta-puzzle. The tasks to be carried out and their sequence are listed in the so-called “lab book” which they have to find in the laboratory. They finish the game by getting a six-digit code which allows them to leave the lab.

The first task within *Eduscape Köln* is to determine the water permeability of a soil sample, see Section 0. Depending on the size of the calculated coefficient, one of six solution paths results from a table in the lab book. The order of the further puzzles is open. A total of ten different laboratory tasks are available, six of which are included in every solution path. So, if students like to play *Eduscape Köln* a second time, the input parameters for the first task have to be changed, which results in another solution path with different laboratory tests.

For each obtained result within the laboratory tests, there is a table in the lab book from which a number for the solution code can be gained. As part of the evaluation of a sieve analysis, for example, the soil group of the tested soil must be determined in accordance with DIN 18196. The result leads to a number for the solution code. Carrying out six laboratory tests results in the six-digit solution code.

In *Eduscape Köln*, students get test data to analyse water permeability, ignition loss, oedometric modulus, shear parameters and Proctor density. To evaluate the degree of compaction by means of dynamic probing light (DPL) results, they watch a video showing a DPL penetrating in the soil and must deduce the correct degree of compaction based on the observed penetration resistance. There are also tests that students have to conduct by themselves – at least in parts. These are the tests in which the abrasiveness, the liquid limit according to Casagrande, the consistency index, the density for minimum and maximum compactness and a grain size distribution have to be determined.

4.2.3 Preparation of students and supervision in the laboratory

The game master prepares the individual tasks and laboratory tests in advance of the eduscape date. When the students enter the lab, they are briefed on the main features of *Eduscape Köln* by the game master. They get a tablet for the dynamic probing task and a collection of tables, which they can also use in their exam. The actual run of *Eduscape Köln* has so far been supervised by a laboratory employee and a student assistant, who occasionally gave hints when the students got stuck.

4.2.4 Results of student participation and feedback

So far, *Eduscape Köln* was played by several groups of students. Students participated voluntarily in order to prepare for their exam. Together with the team of *Academic Development* at University of Applied Sciences Köln, a feedback form was developed for the first runs of *Eduscape Köln*, which the students filled out after completing the game. The suggestions for improving the tasks were incorporated into the current version of the escape room. In general, the students enjoyed playing the game so much that the *Eduscape Köln* will be offered also in future, even if participating in the escape room during the examination phases is definitely a constraint for the students.

4.3 Eduscape Aachen

4.3.1 Target group and integration into the course

The laboratory exercise in soil mechanics is a compulsory part of the module “Soil Mechanics” in the 3rd semester of the civil and timber engineering courses at University of Applied Sciences Aachen, Germany. It teaches the essential tests for the description and classification of soil types and, thus, forms a basis for understanding the subject matter.

For several years, however, there has been a decline in students' motivation to engage with the content before or during the laboratory exercise. With a total of around 20 groups with 8 to 10 participants each, this also led to frustration among the laboratory supervisors. The restructuring of the laboratory exercise into an escape room with subject-related tasks and tricky puzzles was, therefore, intended to significantly increase the students' motivation, even if this was not conceived as a comprehensive replacement for the “classic” laboratory exercise but a voluntary add-on.

4.3.2 Structure and content

In 2020, *Eduscape Aachen* was developed as the first implementation of such an innovative learning concept at the University of Applied Sciences Aachen. Its development was supported by an internal teaching grant to fund personnel and material costs. The first step was to use specialist literature, the Internet and “real” escape room games to determine the basics and to collect ideas for suitable puzzles. Thus, a game concept and a baseline “story” were created.

After analyzing typical game situations and arranging the practical content of the previous laboratory exercise into a logical chain of puzzles, individual puzzles and tasks were refined and coordinated in their sequence. The tasks follow an open path with the aim of unlocking a key hidden in a cylinder in order to “escape” from the laboratory.

In addition to the existing laboratory equipment, other materials (containers, boxes, locks, etc.) were incorporated into the puzzles. Apart from the laboratory test setups required to carry out the tests, it was initially planned to allow the Internet or the Learning Management System ILIAS to be used as a source of information alongside the usual formulae collections from the course. However, this idea was ultimately discarded in order to focus the students on the physical experience.

4.3.3 Preparation of students and supervision in the laboratory

The explanation of standard laboratory tests is covered in the course lectures during the semester to prepare students for *Eduscape Aachen*. As the students in Aachen do not perform all the laboratory tests by themselves due to the high number of participants, the subject-related tasks concentrate on relatively simple evaluations (calculation of water content, analysis of a grain size distribution, determination of the in-situ density, interpretation of a hydrological map).

No separate preparation was required for solving the logic puzzles and for finding the hidden clues. As an additional support element for the participants, a “secret notebook” was developed for *Eduscape Aachen*, in which further hints, assistance but also distractions were documented. During the eduscape in the laboratory, the students were supported by student assistants who acted as game masters and clue-givers if needed.

4.3.4 Results of student participation and feedback

In several rounds of testing, the degree of difficulty, sequence and duration of the tasks and puzzles were worked out together with the student assistants before the concept was tested for the first time in the winter semester 2021/22 with a group of around 10 interested students. It became clear that the tasks are not easy for students who have little experience with escape rooms. *Eduscape Aachen* was then adapted slightly and played through a few more times with subsequent groups of students on a voluntary basis; however, a systematic implementation into the course schedule, as well as evaluation and assessment have not yet taken place due to lack of resources.

4.4 Example tasks

As carrying out soil mechanics laboratory tests is very time-consuming, many calculation puzzles are set in the eduscape presented, in which given measurement results from laboratory tests have to be evaluated. For example, the students have to determine water permeability, go to the corresponding laboratory test and find a piece of paper with the task shown in Figure 3.

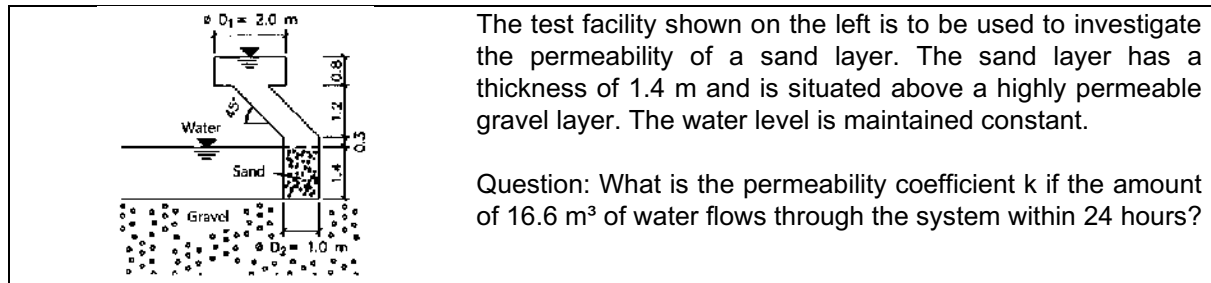


Figure 3: Task for determining the water permeability

In order to create variety and to anchor the laboratory test procedure in the students' minds, physical puzzles are also posed at some points for the solution of which the students have to carry out laboratory tests – or at least parts of them. For example, the percentage of a soil sample passing a 0.2 mm sieve is required to derive a digit for the solution code. The students must recognise that they have to go to the sieve analysis set up. There they find a data sheet covering the retained masses on the sieves with mesh sizes of 63 mm to 0.063 mm, see Figure 4. However, the mass of the soil in the sieve with an opening of 0.2 mm is missing. Instead, the corresponding sieve including a retained mass of soil is next to the data sheet. The students must pour the soil sample from the sieve into a pan, remove individual sand particles with a brush, determine the masses of the empty pan and the pan filled with soil, calculate the difference and enter this in the data sheet. They then have to calculate the percentage passing from the soil mass, whereby the percentage passing of the sieve with an opening of 0.2 mm leads to a digit in the solution code. In this way, they do not carry out a complete sieve analysis but remember the procedure for the sieve analysis by weighing the soil sample once and determining the sieve passages.

As the students should also understand what the results of the different laboratory tests can be used for, they continue to deal with the results from the sieve analysis: they have to draw the grain size distribution of the soil in a diagram and determine the soil group according to DIN 18196. The determined soil group then leads to another digit of the solution code.

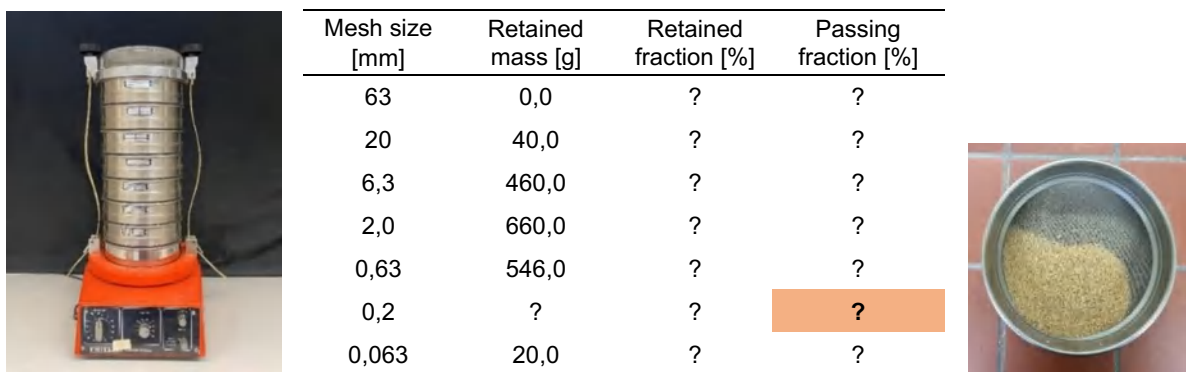


Figure 4. Utensils for the puzzle “sieve analysis” in which the passing fraction of the 0,2 mm mesh to be determined leads to a digit in the solution code

5 Summary and conclusions

The article described the history and characteristics of escape rooms in the entertainment industry as well as the development, structure and challenges of educational escape rooms (eduscapes) that have

evolved from them. The results of a survey conducted among German-speaking geotechnics professors in Germany, Switzerland and Austria on the boundary conditions of soil mechanics laboratory courses were presented. Learning objectives that can be achieved with an eduscape were formulated and three eduscapes developed by the authors were presented.

In conclusion, it can be stated that the presented eduscapes brought great variety into the soil mechanics laboratory courses. The playful confrontation of the students with the laboratory tests results in an intrinsic motivation to master the laboratory tests well. Furthermore, an additional learning effect can be achieved, as students not only carry out and evaluate the tests according to instructions - as in the laboratory course - but they have to decide for themselves which laboratory test is to be used to determine a certain value. This enables a deeper understanding of laboratory tests and their results.

However, this added value also presents challenges. For example, it is not easy to combine purely technical content (namely the standardised execution and evaluation of laboratory tests) and an exciting narrative with entertainment value. In addition, some laboratory tests take a very long time to carry out - sometimes several days - but an escape room should be designed for only one or two hours. The duration of the eduscape games represents further organisational hurdles: as the group size should be limited to a few participants, many runs are necessary for large groups of students. These activities also require a lot of personnel since the groups should be accompanied by laboratory staff.

Even though the design and implementation of such eduscapes pose a number of challenges, they are a means of practising and deepening the content of lectures and practical courses that was rated highly by the students. Interested parties are invited to request a more detailed description of the eduscape layout, required materials and test equipment as well as specific instructions from the authors.

References

- Buchner, J. T. (2022). Lernen mit einem Augmented Reality Escape Game: Der Einfluss didaktischer Variationen auf den Lernerfolg und das Immersionserleben (Learning with an augmented reality escape game: The influence of didactic variations on learning success and the immersive experience). 10.17185/duerpublico/75994.
- DIN 18196 (2023). Erd- und Grundbau – Bodenklassifikation für bautechnische Zwecke (Earthworks and foundation engineering - Soil classification for civil engineering purposes), DIN Deutsches Institut für Normung e.V., 2023
- Fotaris, P., Mastoras, T. (2019). Escape Rooms for Learning: A Systematic Review. Proceedings of the European Conference on Games-Based Learning, pp. 235-243
- Geisler, S. (2024). NoCode-Escape Rooms fuer den Inverted Classroom – Lernerfolg steigern ohne Programmierkenntnisse (NoCode escape rooms for the inverted classroom - increase learning success without programming knowledge). 1. Tag für Lehrende, FH St. Pölten
- Hörsch, H., von Korfflesch, H. F. O., Krath, J., Kohler, J. (2023). Online Educational Escape Rooms – Ein Fallbeispiel (Online Educational Escape Rooms - A case study). In: Mrohs, L., Franz, J., Herrmann, D., Lindner, K., Staake, T. (Eds.): Digitale Kulturen der Lehre entwickeln, pp. 223-244, Springer Fachmedien Wiesbaden (Perspektiven der Hochschuldidaktik).
- Kerres, M. (2018). Mediendidaktik, Konzeption und Entwicklung digitaler Lernangebote (Media didactics, conception and development of digital learning programmes), fifth ed., de Gruyter Oldenbourg, Germany
- Nicholson, S. (2015). Peeking behind the locked door: A survey of escape room facilities. White Paper available at <http://scottnicholson.com/pubs/erfacwhite.pdf>
- Veldkamp, A., van de Grint, L., Knippels, M.-C. P. J., van Joolingen, W. R. (2020). Escape education: A systematic review on escape rooms in education. Educational Research Review 31, p. 100364
- Wenz, J. (2024). Entwicklung eines Escape Rooms für ein geotechnisches Labor (Development of an escape room for a geotechnical laboratory), Mainz University of Applied Sciences
- Wiemker, M., Elumir, E., Clare, A. (2015). Escape Room Games: Can you transform an unpleasant situation into a pleasant one? In Haag, J., Weißenböck, J., Gruber, W., Christian, M., Freisleben-Teutscher, C. (Eds.), Game based learning, pp. 55-68

Authors' bios

Katharina Kluge, University of Applied Sciences Mainz (Germany)

Dr. Katharina Kluge is full professor at the University of Applied Sciences Mainz, Germany, where she teaches geotechnical engineering since 2013. She graduated in industrial engineering / civil engineering from Technical University of Braunschweig, Germany, (2003) and obtained a Ph.D. in an International Research Training Group run by Technical University of Braunschweig, Germany, in conjunction with Università degli Studi di Firenze, Italy (2007). From 2007 to 2013 she worked for Bilfinger Berger on geotechnical engineering projects before transferring to University of Applied Sciences Mainz in 2013.

Katharina is program director of the civil engineering bachelor's degree at Hochschule Mainz and chair of the Technical Committee "Water/Soil/Environment" of the German Association of Departments of Civil Engineering and Environmental Engineering at Universities of Applied Sciences. In 2022, together with the second and third authors she founded the Network "GeNlaL" (Geotechnics Network for Innovations in Teaching) in which about a third of the geotechnical engineering professors from Germany, Switzerland and Austria regularly meet and exchange ideas on teaching topics. Her expertise includes inverted classroom teaching, interactive online tools and innovative laboratory courses, for example.

Christoph Budach, University of Applied Sciences Köln (Germany)

Dr. Christoph Budach is full professor at the University of Applied Sciences Köln, Germany, who specialises in the field of geotechnical engineering and tunneling. He graduated in civil engineering from Ruhr-University Bochum (RUB) and obtained a Ph.D. with the focus of mechanized tunneling in soft soils by RUB in 2011. Between 2011-2019 he worked for HOCHTIEF Solutions AG and HOCHTIEF Infrastructure GmbH as well as for ELE Beratende Ingenieure GmbH. Since 2019, he is professor for geotechnical engineering at University of Applied Sciences Köln, Germany. Since several years, he has experience in inverted classroom teaching and innovative laboratory courses, for example. In 2022, together with the other authors he founded the Network "GeNlaL". Christoph Budach is a member of the German Committee for Underground Construction and is represented on other committees. He has published numerous publications in the field of tunneling, geotechnical engineering and teaching.

Ansgar Kirsch, University of Applied Sciences Aachen (Germany)

Dr. Ansgar Kirsch is a full professor of geotechnical engineering at the University of Applied Sciences in Aachen, Germany, responsible for teaching soil mechanics and (under)ground engineering since 2015. He holds a civil engineering diploma from RWTH Aachen (2004) and an International Diploma from Imperial College London (2002). He earned his PhD from the University of Innsbruck, Austria, (2008) and worked at ILF Consulting Engineers in Innsbruck (2010–2015) before transitioning to academia.

Passionate about teaching and student engagement, he has served as vice-dean for teaching since 2018 and contributes to various university boards on higher education. As member of the national teaching network "Lehre^n" and co-founder of the "GeNlaL" Network, he actively promotes digital and interactive learning. His commitment to educational innovation has been recognised through multiple awards, including the 2022 university teaching award and the 2018 Fellowship for Digital Higher Education in NRW. His expertise includes inverted classroom, interactive online tools and STACK programming.

The integration of environmental considerations into Geotechnical Engineering Education: Balancing optimization and sustainability

U. S. Okayay

Group INFRANEO, Pantin, France
us.okyay@infraneo.com

ABSTRACT: Balancing technical performance with environmental sustainability is becoming a central challenge in geotechnical engineering. Traditional design methods often assume negligible displacements, leading to overly conservative and resource-intensive solutions. In contrast, accepting moderate displacements—when compatible with structural performance—can enable more economical and sustainable designs. This paper explores how such optimization strategies can be integrated into geotechnical engineering education. Techniques including rigid inclusions, soil reinforcement, and performance-based design are presented as means to reduce material consumption without compromising stability. Numerical modelling and project-based learning are emphasized as essential tools for teaching these trade-offs. Real-world case studies illustrate how students can assess structural performance, quantify environmental impact, and develop holistic design approaches. The paper underscores the importance of embedding environmental considerations into geotechnical curricula to prepare engineers capable of delivering resilient, cost-effective, and sustainability-driven infrastructure.

Keywords: Sustainability, Optimization, Settlement, Reinforcement, Modelling

1 Introduction

As sustainability becomes a global priority, geotechnical engineers are increasingly tasked with delivering infrastructure that is both resilient and environmentally responsible. This challenge extends to education, where future engineers must be equipped not only with technical expertise but also with an understanding of environmental trade-offs.

Traditional design approaches often rely on conservative assumptions, such as zero settlement, leading to overdesigned and resource-intensive solutions. In contrast, performance-based methods that allow controlled settlements—when structurally acceptable—enable more sustainable outcomes. Techniques like reinforced soil systems and rigid inclusions can reduce dependence on deep foundations, cutting material use and environmental impact.

To embed these principles in education, numerical modelling and project-based learning are essential. They allow students to explore soil–structure interaction under varied conditions and assess the trade-offs between performance, cost, and sustainability. These experiences foster innovation and prepare graduates to develop efficient, environmentally conscious geotechnical solutions (Kibert, 2008).

2 Integrating environmental considerations into geotechnical decision-making

Geotechnical engineering has traditionally focused on technical performance and cost efficiency. However, growing environmental concerns now demand a more holistic approach that balances structural stability, economic viability, and sustainability (Basu et al., 2014). This shift requires rethinking established practices and embedding environmental considerations into each phase of design and construction.

Conventional solutions often rely on deep foundations and rigid safety assumptions that, while structurally conservative, result in excessive material use and a high carbon footprint. Performance-based design enables engineers to accept controlled settlements within safe limits, reducing overdesign. Sustainable alternatives such as rigid inclusions, ground improvement, and geosynthetic reinforcement optimize resource use while maintaining stability. Contemporary geotechnical practice incorporates sustainability through strategic material choices, bioengineering, and flexible structural systems.

Recent studies such as Ottaviani et al. (2024) have emphasized the growing role of carbon calculators in quantifying environmental impact, especially in the design of geosynthetic-based solutions. Educating future geotechnical engineers requires integrating sustainability across the curriculum. Numerical modelling, quantified case studies, and design-performance assessments foster a deep understanding of environmental trade-offs. Project-based learning allows students to engage with real-world constraints and evaluate multiple design paths based on technical and ecological performance.

3 Optimized solutions: Balancing technical efficiency with environmental sustainability

A sustainable approach requires balancing technical efficiency, cost-effectiveness, and ecological responsibility. One key shift involves accepting controlled settlements and adopting alternative reinforcement methods, which can significantly reduce resource consumption while maintaining structural integrity. This section presents optimized geotechnical solutions that achieve this balance, with real-world case studies illustrating their successful application.

3.1 Principles of sustainable geotechnical design

To integrate sustainability into geotechnical engineering, optimized solutions must adhere to key design principles:

- **Resource Efficiency:** Minimize material usage by optimizing foundation design, limiting excavation, and reusing existing soil where possible.
- **Performance-Based Design:** Allow for moderate settlements within safe limits to reduce reliance on deep foundations and heavy reinforcement.
- **Soil Reinforcement & Ground Improvement:** Implement techniques such as rigid inclusions, geosynthetics, and ground stabilization to enhance soil performance while reducing environmental impact.
- **Minimizing Environmental Disruption:** Prioritize construction methods that reduce soil disturbance, groundwater contamination, and carbon emissions.

The following sections analyse specific geotechnical solutions that embody these principles.

3.1.1 Case Study 1: Rehabilitation of historic buildings and foundation reinforcement

Reinforcing historic building foundations presents the dual challenge of ensuring structural stability while preserving architectural integrity. Traditional replacement methods are invasive, resource-intensive, and often unsustainable. In contrast, targeted reinforcement techniques—such as micropiles and high-pressure grouting—can redistribute loads and enhance bearing capacity with minimal excavation (Leung et al., 2011). As shown in Figure 1, these methods offer a more sustainable alternative, improving load performance while reducing material use and environmental disruption.

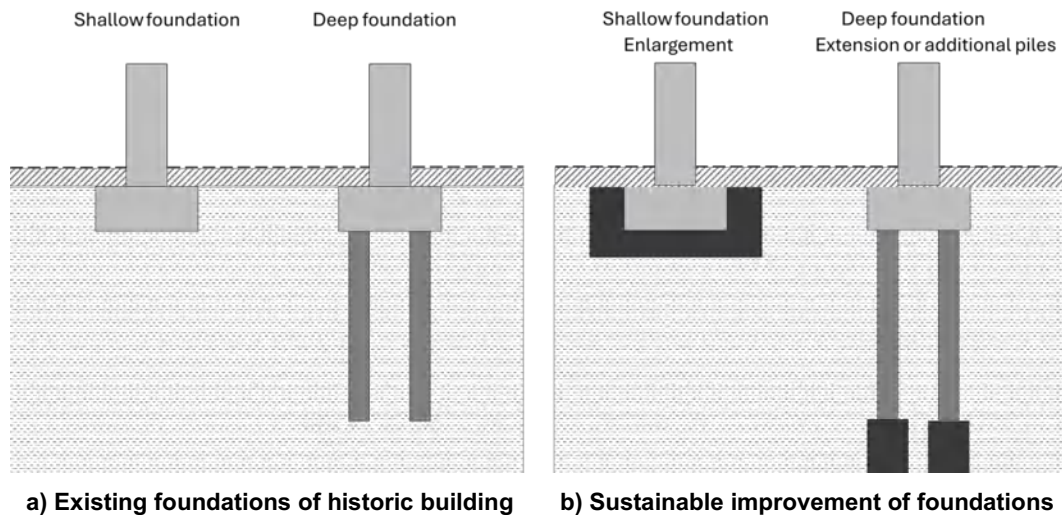


Figure 1. Reinforcement techniques for enhancing load-bearing capacity

These reinforcement strategies optimize resource efficiency, reduce carbon emissions, and limit construction waste. Moreover, geotechnical modelling and real-time monitoring enable engineers to refine reinforcement strategies, ensuring long-term structural stability while minimizing environmental impact (Misra & Basu, 2011).

Example: Rehabilitation of Historic Structures and Foundation Reinforcement – The Macdonald Warehouse Project, Paris

This case study presents the transformation of the Macdonald warehouse complex in Paris (originally built in the 1970s) into a mixed-use facility including residential units, offices, and public services. The building's dimensions (600 x 60 meters) and its founding conditions—on approximately 500 piles embedded in Saint-Ouen limestone overlying Beauchamp sands—posed significant geotechnical and structural challenges. To meet the demands of the planned superstructure extensions, a hybrid foundation reinforcement strategy was adopted.

Following a thorough diagnostic campaign, it was determined that approximately 75% of the existing piles could be reused if their load-bearing capacity was enhanced. High-pressure jet grouting was selected as the primary technique for reinforcing the pile tips. Columns with a diameter of 1.3 meters and a length of 3 meters were installed directly through the existing piles using rotary drilling and high-pressure cementitious injection. In addition to jet grouting, 2,700 new micropiles, each 8 meters long, were installed to support the new vertical structural elements such as elevator shafts and stairwells.

These micropiles served both to redistribute loads and to mitigate settlement risks in areas subject to differential loading. Field load tests on both individual and grouped micropiles validated the design assumptions and ensured compatibility with the existing foundation system. The cross-sectional layout of the Macdonald warehouse project, as shown in Figure 2, presents the combined use of jet-grouting columns and new micropiles within the site's geological stratigraphy. This configuration illustrates how hybrid foundation solutions can be effectively adapted to complex ground conditions while preserving existing infrastructure.

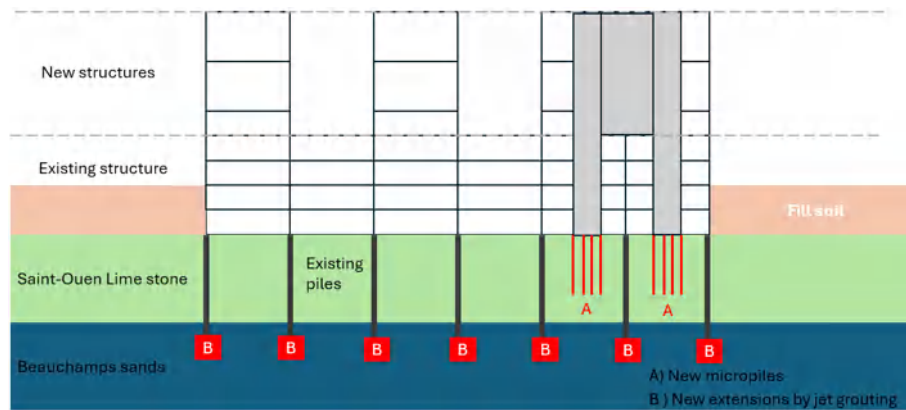


Figure 2. Cross-sectional diagram of the Macdonald foundation system showing jet-grouting columns, new micropiles, and geological stratigraphy.

This project exemplifies how targeted foundation reinforcement—through a combination of reuse, high-pressure grouting, and micropile implementation—can ensure long-term structural performance with minimal environmental disruption. By limiting demolition, excavation, and material waste, the Macdonald warehouse rehabilitation also contributes to broader sustainability goals. This project was conducted during the author’s time at Terrasol, where our team was responsible for the geotechnical diagnosis and foundation reinforcement design for the transformation of the Macdonald Warehouse into a mixed-use development.

3.1.2 Case Study 2: Settlement-tolerant foundation systems with soil improvement

The design of industrial foundations—such as for tanks, reservoirs, and wind turbines—often targets strict settlement limits. Traditional deep foundations minimize differential settlement but at high material and environmental cost. Where moderate settlements are tolerable, soil improvement methods offer more sustainable alternatives (Okyay et al., 2012).

Rigid inclusions, such as controlled modulus or grouted stone columns, enhance soil capacity and optimize load transfer (Okyay et al., 2010). Preloading and geosynthetic reinforcement further reduce post-construction settlement and distribute loads efficiently. As shown in Figure 3, these strategies reduce material use and environmental impact while preserving structural performance.

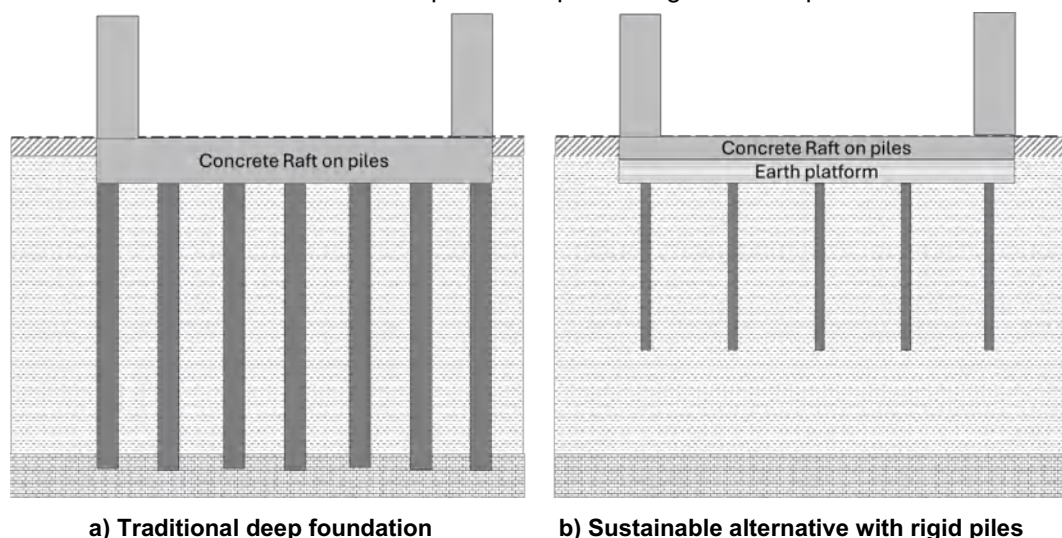


Figure 3. Comparison between a traditional deep foundation and a sustainable alternative

By integrating these soil improvement strategies, engineers can reduce reliance on deep foundations while maintaining structural performance. This approach lowers carbon emissions by decreasing concrete and steel usage and minimizes excavation-related environmental impacts. Furthermore, optimizing foundation design to tolerate moderate settlements within safe limits reduces construction costs and leads to more resource-efficient geotechnical solutions.

Example: Sustainable Foundation Design for a Water Treatment Plant in Pont-Audemer, France

A full-scale geotechnical study was carried out to evaluate the performance of rigid inclusions as a soil reinforcement technique beneath a large-diameter concrete water tank at the Pont-Audemer water treatment facility in northern France. The site was characterized by deep, compressible soft soils underlying a superficial fill layer, posing significant challenges in terms of settlement control and structural stability. Conventional deep foundation solutions were deemed economically and environmentally inefficient for this context. Instead, a more sustainable alternative was implemented: the foundation system employed rigid inclusions with a diameter of 28 cm, installed in a 3 m × 3 m grid, extending through the soft soil strata. To facilitate effective load distribution and settlement control, a cement-stabilized earth-platform was constructed above the inclusions. This platform served as a critical load transfer medium, allowing vertical stresses from the tank structure to be partially distributed across both the inclusions and the surrounding soil. The design promoted a composite behaviour that enhanced bearing capacity while limiting differential settlement. Figure 4 provides both the plan and final views of the water treatment tank constructed in Pont-Audemer, France.

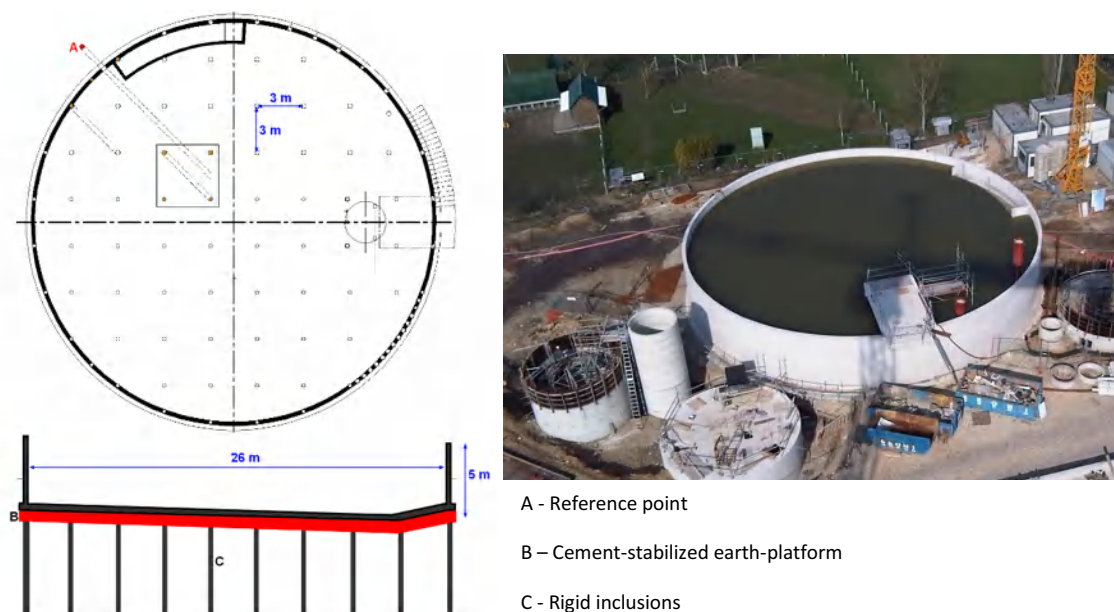


Figure 4. Plan and final views of the structure (from PINTO)

The site was extensively instrumented with settlement sensors and earth pressure cells strategically placed beneath both the centre and perimeter of the tank. These instruments enabled continuous monitoring of vertical displacements and stress distribution throughout the construction and operational phases. The collected field data were further analysed and validated through advanced three-dimensional numerical modelling using Ansys, which accurately simulated the soil–structure interaction under cyclic loading conditions. The monitoring results revealed that the maximum settlement at the tank centre was limited to 17 mm, remaining well within the design serviceability threshold of 20 mm (Figure 5). This demonstrated the system's ability to effectively control differential settlements and confirmed the reliability of the inclusion-based reinforcement strategy under realistic loading scenarios.

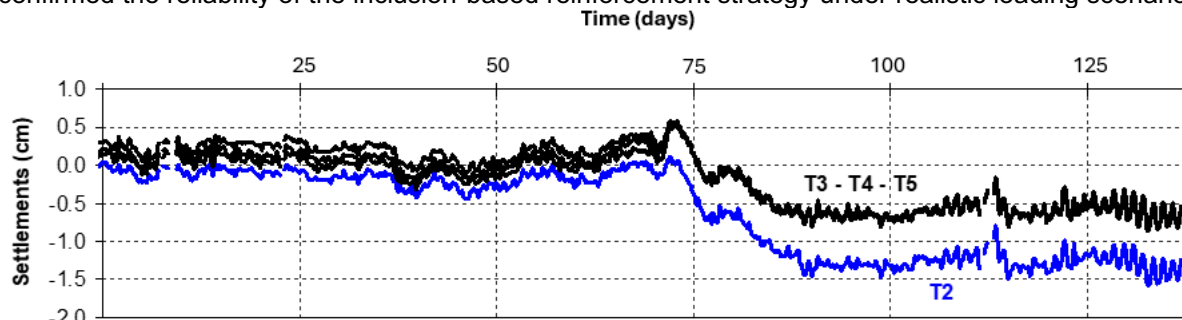


Figure 5. Settlement under the centre of the water concrete tank

Field measurements also indicated that vertical stresses at the heads of the rigid inclusions consistently ranged between 1500 and 1600 kPa, confirming efficient stress transfer from the structure to the reinforced soil system (Figure 6). This stress concentration demonstrated the effectiveness of the inclusions in mobilizing load-bearing capacity while minimizing stress propagation to the surrounding compressible soil.

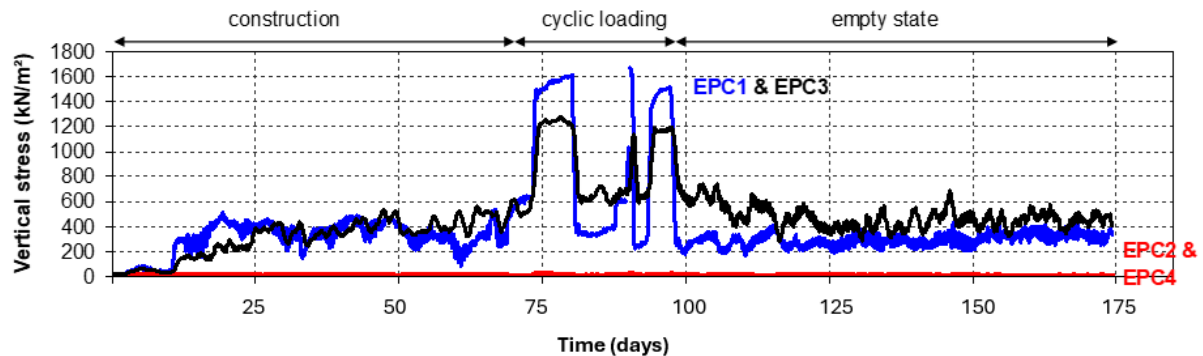
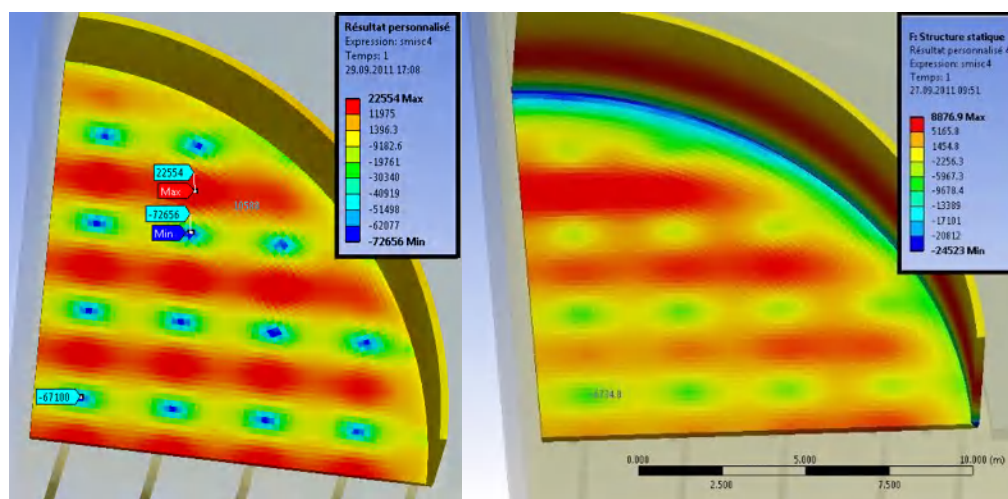


Figure 6. Stress distribution at inclusion head and soil

Long-term monitoring under repeated cyclic loading conditions confirmed the stabilization of settlements over time, with no observable degradation in structural performance or loss of load transfer efficiency. This demonstrated the durability and resilience of the rigid inclusion system under service loading scenarios representative of operational conditions for water storage infrastructure. Further structural analysis revealed a significant reduction in bending moments within the raft foundation when rigid inclusions were used in place of conventional piles. Figure 7 illustrates the bending moment distributions on raft foundations using two different reinforcement strategies—piles and rigid inclusions. The comparison demonstrates how the use of rigid inclusions significantly reduces internal forces, resulting in a more efficient and sustainable structural response. Numerical simulations showed that, with piles, the maximum negative moment at support was $-72.6 \text{ kN}\cdot\text{m}$, and the maximum positive moment in span was $+22.6 \text{ kN}\cdot\text{m}$. In contrast, when rigid inclusions were employed, the maximum negative moment at support was reduced to $-6.7 \text{ kN}\cdot\text{m}$, and the maximum positive moment in span decreased to $+8.9 \text{ kN}\cdot\text{m}$. This substantial reduction in internal forces indicates that rigid inclusions significantly alleviate structural demand on the raft, contributing to a more economical and durable foundation design.



a) Bending moments on raft with piles

b) Bending moments on raft with rigid inclusions

Figure 7. Reinforcement techniques for enhancing load-bearing capacity

Replacing deep piles with rigid inclusions at Pont-Audemer yielded a 35% reduction in concrete use and over 25% lower CO_2 emissions, while minimizing excavation and spoil transport. This approach significantly reduced the project's environmental footprint.

Educationally, the case offers rich material for performance-based learning. Students can analyse real monitoring data, simulate soil–structure interaction using FEM tools, and compare traditional and optimized designs. Tools like the IGS Carbon Calculator enable environmental impact quantification, helping students balance performance and sustainability in design decisions. This project was carried out during the author's time at PINTO, where I was involved in the geotechnical design and monitoring of the rigid inclusion system beneath a large water storage tank at the Pont-Audemer treatment facility.

3.1.3 Flexible retaining structures as an alternative to rigid concrete walls

Retaining structures are vital for slope stabilization and soil retention in geotechnical design. Traditional concrete walls provide strength but require deep foundations, extensive materials, and drainage systems. They are also vulnerable to cracking under settlement or seismic loads.

As shown in Figure 8, flexible retaining systems—such as MSE walls, gabions, and soil-nailed walls—offer sustainable alternatives. These systems use geosynthetics and natural drainage to reduce material use and adapt to ground movement. MSE walls reinforce backfill with geogrids, allowing controlled deformation and reducing excavation. Gabions offer permeable, low-cost solutions ideal for riverbanks and erosion control. Soil-nailed systems, combining steel bars and geosynthetic facings, are particularly effective in confined urban excavations (Elias & Juran, 1991). These solutions reduce environmental impact, improve adaptability, and support sustainable design in diverse contexts.

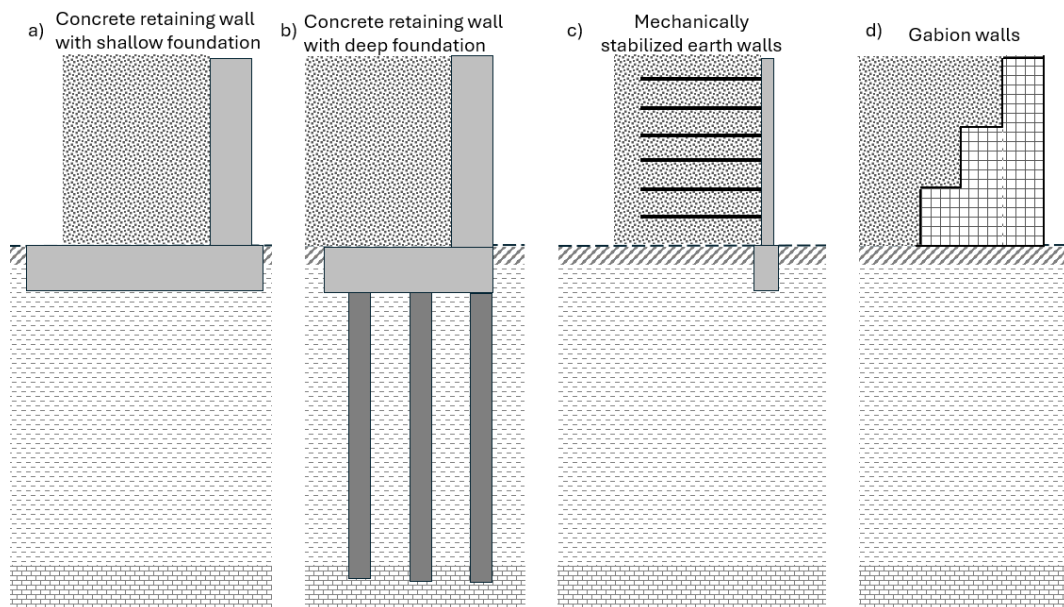


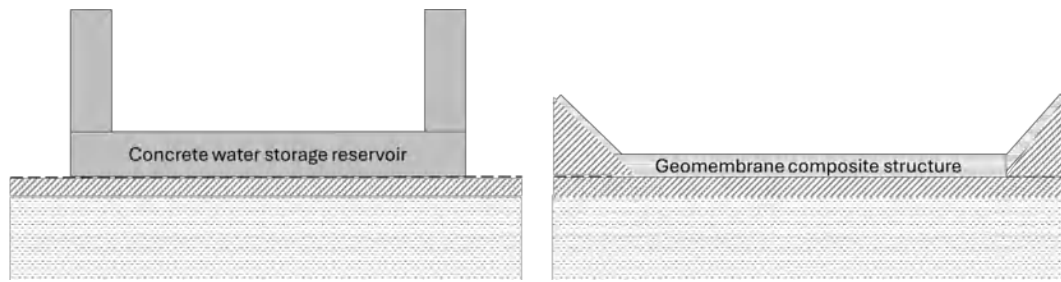
Figure 8. Comparison of retaining walls: rigid vs. flexible solutions

Compared to traditional concrete walls, flexible retaining structures require fewer raw materials, are more adaptable to settlements, and have a lower carbon footprint. Their ability to integrate with natural landscapes and improve long-term performance makes them a preferred choice for sustainable geotechnical solutions.

3.1.4 Case Study 4: Water storage basins – Large raft foundations vs. Geomembranes

The design of water storage basins is critical in geotechnical engineering, requiring impermeability, structural durability, and stability in various ground conditions. Traditionally, reinforced concrete slabs have been used as foundation systems for basins, providing a rigid and watertight base. While effective, these structures demand high material consumption, extensive excavation, and significant carbon emissions due to the use of concrete and steel. Additionally, in compressible or weak soils, differential settlement can cause cracking and loss of structural integrity, leading to costly repairs and water leakage (Han et al., 2020). A sustainable and adaptable alternative is the use of geomembrane-lined basins, which employ synthetic liners. These flexible membranes create a quasi-impermeable barrier that prevents seepage while conforming to ground deformations, reducing the risk of settlement-induced failure. Compared to rigid concrete slabs, geomembranes require minimal excavation, eliminate the need for deep foundations, and significantly lower material costs. Figure 9 contrasts a classical concrete

foundation system with a sustainable alternative incorporating geomembranes. This comparison underscores how geosynthetic solutions can achieve comparable performance while significantly reducing the carbon footprint and material demand of foundation systems.



a) Concrete structure with classical design b) Geomembrane-lined basin as a sustainable alternative

Figure 9. Comparison of (a) a rigid concrete foundation and (b) a sustainable geosynthetic solution for water storage.

Geomembrane-lined basins also offer superior chemical resistance and durability, making them ideal for industrial wastewater storage, irrigation reservoirs, and landfill liners. Unlike concrete, which can degrade over time due to chemical exposure, geomembranes maintain their integrity under harsh environmental conditions, extending service life and reducing maintenance costs. A key advantage of geosynthetic drainage layers is their ability to enhance stability by reducing uplift pressures and preventing liner displacement. Compared to traditional concrete slabs, geomembrane liners offer a lower-carbon, cost-effective, and more resilient solution for water storage applications. Their ability to adapt to varying soil conditions, resist cracking, and reduce material consumption makes them a preferred choice in sustainable geotechnical engineering.

3.1.5 Case Study 5: The new Austrian tunnelling method (NATM) versus conventional tunnel support systems

Tunnelling is one of the most complex challenges in geotechnical engineering, particularly in soft or weak ground conditions, where maintaining stability while minimizing material use is a key concern. Conventional tunnelling methods typically rely on rigid support systems, such as precast segmental lining, steel ribs, or immediate application of thick shotcrete layers. These techniques are based on the assumption that tunnel linings must fully bear the surrounding ground load, often leading to over-conservative designs, excessive reinforcement, and increased project costs. In contrast, the New Austrian tunnelling Method (NATM) takes a fundamentally different approach by utilizing controlled ground deformations to redistribute stresses, allowing the surrounding soil or rock to actively contribute to tunnel stability (Figure 10). This method enables a more flexible and resource-efficient tunnelling process, making it a preferred choice for sustainable infrastructure projects (Jenny et al., 1987).

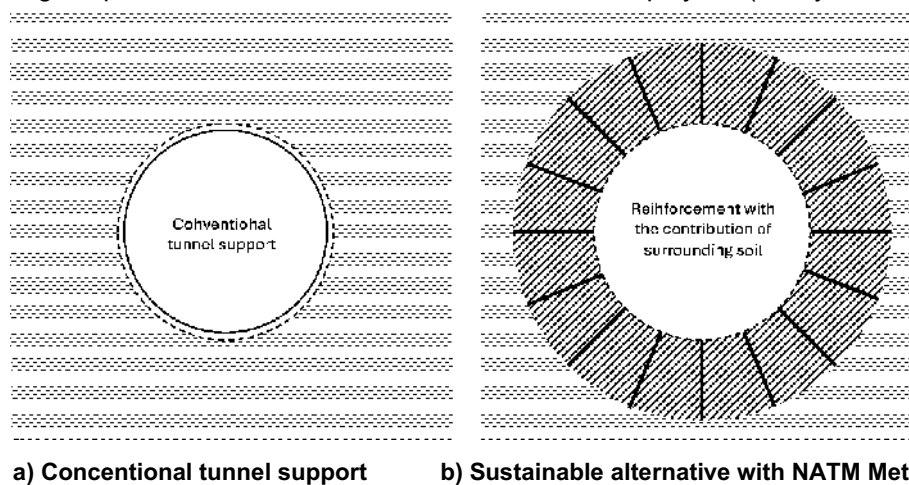


Figure 10. Comparison of conventional tunnel retaining methods and reinforced soil techniques

In comparison to traditional tunnelling techniques, NATM significantly improves material efficiency, excavation control, and adaptability to varying geological conditions. Conventional tunnelling often relies

on full-face excavation with pre-determined thick linings, leading to excessive material use and higher project costs. NATM, on the other hand, integrates sequential excavation with progressive support adjustments, leading to cost savings and improved safety margins. The ability to incorporate controlled deformations ensures that the surrounding rock mass plays an active role in supporting the tunnel, reducing the demand on structural reinforcements.

By allowing engineers to make real-time adjustments based on observed site conditions, NATM aligns with modern performance-based design principles, ensuring that tunnel construction is not only structurally sound but also resource-efficient. The reduced reliance on rigid pre-designed supports makes it particularly well-suited for projects where sustainability and material conservation are priorities. As geotechnical engineering moves toward more sustainable construction practices, the principles of NATM serve as a model for integrating adaptive design, real-time monitoring, and optimized material use in underground infrastructure development.

3.1.6 Case Study 6: Optimizing geotechnical design through the observational method

Geotechnical design often faces uncertainty due to variable soil and rock conditions. Traditional approaches rely on high safety factors, leading to overdesign, excess material use, and higher costs. The observational method (Peck, 1969) offers a more adaptive strategy: designs are based on expected conditions with contingency plans that adjust in real time as site data evolves. Instrumentation—such as inclinometers, piezometers, and settlement gauges—guides these adjustments, enabling targeted reinforcement only where needed and reducing environmental impact (Okyay et al., 2012). A practical application was during the EOLE project in Paris, where compensation grouting stabilized existing buildings during tunnel excavation by offsetting settlements in real time (Figure 11). This method exemplifies sustainable, performance-based design under urban constraints.

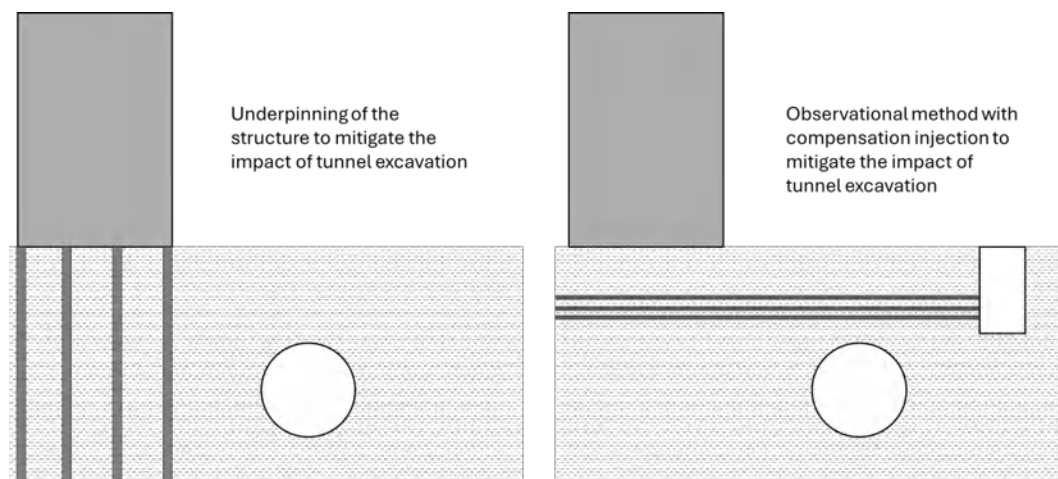


Figure 11. Example of the observational method with settlement compensation

Widely used in excavations, tunnelling, and slope stabilization, the observational method is especially effective in urban settings to minimize settlements and protect adjacent structures. By enabling performance-based adjustments, it reduces material use and supports sustainability.

While it requires skilled teams and robust monitoring, its successful implementation enhances adaptability, lowers costs, and significantly cuts the environmental footprint of geotechnical projects.

4 Concluding remarks

The future of geotechnical engineering lies in its ability to respond to global sustainability challenges through innovation, efficiency, and environmental responsibility. As infrastructure demands grow and climate constraints intensify, engineers must be equipped not only with technical competence but also with the mindset to develop resource-conscious solutions that minimise impact without compromising safety or performance.

This paper has demonstrated that sustainable geotechnical design is not an abstract concept but a practical reality—achievable through performance-based methods, smart material use, and integrated environmental assessment. Case studies presented here illustrate how technologies such as rigid inclusions, geosynthetics, geomembranes, and observational design can significantly reduce carbon footprints, construction waste, and material consumption.

To prepare future engineers for this paradigm, geotechnical education must evolve. Curricula should emphasise:

- Analytical tools for quantifying environmental impact (e.g. carbon calculators),
- Simulation-based learning for design trade-offs,
- Case-driven teaching grounded in real projects, and
- Interdisciplinary collaboration to understand broader system interactions.

Embedding sustainability into geotechnical education ensures that graduates are not only capable designers but also critical thinkers who can balance performance, cost, and environmental goals in a rapidly changing world. This transformation is essential if geotechnical engineers are to lead the profession in delivering infrastructure that is resilient, responsible, and future-ready.

References

- Basu, D., Misra, A., Puppala, A.J. (2014). Sustainability and geotechnical engineering: perspectives and review. *Canadian Geotechnical Journal*, 52(1), pp. 96–113.
- Elias, V., Juran, I. (1991). Soil Nailing for Stabilization of Highway Slopes and Excavations. Federal Highway Administration, Report No. FHWA-RD-89-198, Washington, D.C., USA.
- Han, X., Wang, X., Zhu, Y., Huang, J., Yang, L., Chang, Z., Fu, F. (2020). An experimental study on concrete and geomembrane lining effects on canal seepage in arid agricultural areas. *Water*, 12(9), pp. 2343.
- Jenny, R.J., Donde, P.M., Wagner, H. (1987). New Austrian Tunneling Method used for design of soft-ground tunnels for Washington Metro. *Transportation Research Record*, (1150), pp. 11–18.
- Kibert, C.J. (2008). *Sustainable Construction*, second ed. John Wiley and Sons Inc., New Jersey, USA.
- Leung, Y.F., Soga, K., Klar, A. (2011). Multi-objective foundation optimization and its application to pile reuse. *Proceedings of GeoFrontiers 2011*, Dallas, Tex., USA, pp. 75–84.
- Misra, A., Basu, D. (2011). Sustainability metrics for pile foundations. *Indian Geotechnical Journal*, 41(2), pp. 108–120.
- Okayay, U.S., Dias, D., Thorel, L. (2012). Monitoring of a rigid inclusion reinforced concrete water tanks. *Proceedings of the 3rd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering*, Near East University, Nicosia, North Cyprus, 29 June 2012.
- Okayay, U.S., Dias, D., Thorel, L. (2010). Use of lime and cement treated soils as pile supported load transfer platform. *Engineering Geology*, 114(1–2), pp. 34–44.
- Ottaviani, A., de Melo, D., Bruni, L., Gupta, R., Nelsen, C. (2024). 10 years of carbon calculator use: what have we learned for the future? *Proceedings of the XVIII ECSMGE 2024 – Geotechnical Engineering Challenges to Meet Current and Emerging Needs of Society*, pp. 204–209, Taylor & Francis, Rome, Italy.
- Peck, R.B. (1969). Advantages and limitations of the observational method in applied soil mechanics. *Géotechnique*, 19(2), pp. 171–187.

Author's Bio

Umur Salih OKYAY, Group INFRANEO, France

Dr. Umur Salih OKYAY is a Civil Engineer with a Ph.D. in Geotechnical Engineering and a certified professional geologist. With extensive experience in structural engineering and complex infrastructure projects, he has contributed to the design, analysis, and supervision of major civil engineering works, including bridges, underground structures, high-rise buildings, hydraulic infrastructures, and deep

excavations. Throughout his career, he has worked closely with both public and private institutions, providing innovative solutions to complex engineering challenges.

Beyond his professional engagements, Dr. OKYAY has a deep passion for education and knowledge dissemination. He has been actively involved in higher education for over a decade, teaching in various engineering schools and universities. His courses cover key topics such as soil and rock mechanics, ground improvement, geotechnical structures, and sustainable engineering solutions. He integrates real-world case studies into his teaching, offering students a practical perspective on the challenges and advancements in geotechnical engineering.

Dr. OKYAY has published multiple research articles in international journals and has presented his work at numerous national and international conferences. He is an active member of several prestigious organizations, including the French Committee for Soil Mechanics, the International Society for Soil Mechanics and Geotechnical Engineering.

Through his teaching and research, Dr. OKYAY aims to bridge the gap between academia and industry, ensuring that future engineers acquire the necessary skills to address the evolving challenges of geotechnical engineering and infrastructure resilience. His dedication to education and mentoring contributes significantly to the development of the next generation of civil engineers.

A design project on retaining wall design methods adopting comprehensive site investigation and laboratory testing

E. Theron, J.D. Steenkamp, S.G. Waters & P. Vosloo

Central University of Technology, Free State, Bloemfontein, South Africa

etheron@cut.ac.za, jsteeenkamp@cut.ac.za, swaters@cut.ac.za, pvosloo@cut.ac.za

ABSTRACT: This paper highlights the urgent need for effective geotechnical engineering education to equip students with practical skills for real-world challenges. It focuses on a comprehensive design project undertaken by students at a South African University of Technology. It involved a thorough geotechnical site investigation, laboratory testing, and the design of a cantilever retaining wall. Students engaged in soil sampling and various tests, including Atterberg limits, to assess soil properties and parameters essential for design. The project employed a multi-method approach, comparing manual calculations, Excel spreadsheets, and Geo5 software to enhance understanding and efficiency. Key findings indicate that integrating practical fieldwork with diverse design methodologies significantly enriches students' comprehension of soil mechanics and its applications in engineering. The study underscores the importance of familiarising students with traditional and modern design tools, preparing them for the evolving demands of the profession. This model can serve as a valuable framework for other institutions aiming to strengthen geotechnical engineering education, particularly in regions with limited access to advanced technologies.

Keywords: Retaining wall design, Practical skills, Real-world challenges, Multi-method approach

1 Introduction

The cornerstone of effective engineering education lies in equipping students with practical skills that bridge the gap between theoretical knowledge and real-world applications (Abdel Rahman, 2023). This is particularly vital in geotechnical engineering, where every structure interfaces directly with the ground, making soil behaviour a fundamental consideration. Engineering challenges are inherently complex, demanding hands-on problem-solving skills that extend beyond textbook principles. Real-world scenarios rarely align perfectly with textbook assumptions, necessitating adaptability and practical experience (Ferguson & Kwan, 2021a). Consequently, the engineering industry seeks graduates capable of effectively applying theoretical knowledge in field and laboratory settings. Unlike structural or mechanical components, soil is a naturally occurring material with high variability, requiring thorough investigation and testing. The engineering properties of soil, such as strength, compressibility, and permeability, dictate the stability of any structure. Subsurface conditions significantly affect design decisions; for instance, unsuitable soil conditions can lead to differential settlement or failure. Many geotechnical failures result from inadequate soil investigations or a misunderstanding of soil properties (Day, 2015). Incorporating practical projects, such as the one outlined in the Design Project, ensures students gain hands-on experience in geotechnical site investigations (assessing soil conditions, mapping groundwater levels), laboratory testing (Atterberg limits, shear strength, settlement characteristics), and structural design integration (ensuring proper foundation and retaining wall designs based on site conditions).

2 Literature review

Geotechnical engineering relies heavily on the investigation of the site and laboratory testing to gather essential data about soil conditions for informed foundation design and decision-making (Douglas Partners, 2024; OzGeos, 2024; Sinclair, 2024). Laboratory tests for determining Atterberg Limits provide crucial insights into soil behaviour. The Plastic Limit, a key component of Atterberg Limits, defines the moisture content at which soil transitions from plastic to brittle states, thereby classifying cohesive soils and predicting their behaviour under load (Das, 2010; Navaz et al., 2022; UTA, 2024). Furthermore, the Oedometer test measures soil settlement characteristics under load, which is particularly essential for clayey soils where long-term settlement is a significant concern (Ferguson & Kwan, 2021). The triaxial test assesses soil shear strength under varying confining pressures, yielding parameters like cohesion and friction angle that are pivotal for the stability analysis of foundations and retaining walls (Ferguson & Kwan, 2021b; Keller & Dexter, 2020).

Retaining wall design is a fundamental component of foundation engineering, making it a practical and multifaceted case study for geotechnical analysis. Retaining walls are structures designed to resist lateral earth pressures exerted by soil, particularly in scenarios involving slopes, excavations, or structural load support (Coduto, 2001; Budhu, 2015). The design of retaining walls integrates key foundation engineering principles, including stability analysis against overturning, sliding, and bearing capacity failure. Furthermore, retaining wall design often requires consideration of unsaturated soil mechanics, as the soil behind the wall is rarely fully saturated, and soil suction can significantly influence lateral earth pressures (potentially increasing or decreasing them depending on soil type and environmental conditions) (Smith & Jones, 2023; Toll, 2001). Stability calculations rely on soil properties obtained from laboratory and in-situ tests, ensuring that design parameters align with real-world geotechnical conditions, whether saturated or unsaturated. As foundation design considers vertical and lateral forces acting on a structure, retaining walls are ideal for students to understand load distribution, soil-structure interaction, and engineering safety factors (Bowles, 1996; Diwalkar, 2020; Shrawankar & Gangwal, 2024). By incorporating soil testing results, such as those from Atterberg Limits, Oedometer, and shear strength tests, retaining wall design exercises bridge theoretical knowledge with practical engineering applications.

Utilising geotechnical software applications has become standard practice in engineering design, enabling more precise modelling of soil behaviour and structural interactions. Software applications such as GEO5, PLAXIS, Rocscience, and SLOPE/W offer advanced tools for stability analysis, finite element modelling, and predicting foundation settlement (Geo5, 2024; Rocscience, 2024). These programmes integrate geotechnical theories and empirical models to automate complex calculations, providing engineers with a dependable means of verifying manual design methods while optimising material usage and cost efficiency. Moreover, geotechnical software enhances students' learning by offering visualisation tools, sensitivity analysis, and real-time parametric adjustments, thus improving their ability to interpret and analyse soil-structure interactions (Moore, 2012).

GEO5 is a geotechnical software suite that facilitates designing and analysing various foundation and earth-retaining structures. The software employs principles from limit equilibrium methods and numerical modelling to evaluate stability concerns such as overturning, sliding, and bearing capacity failures (Geo5, 2024). GEO5 enables engineers to input soil parameters, structural loads, and geometric configurations, automatically generating factor of safety values for different failure modes. By streamlining the computational process, the software reduces human error and allows for the rapid evaluation of alternative designs. Additionally, GEO5 integrates industry-standard soil classification systems and laboratory test results, ensuring that geotechnical properties such as shear strength, plasticity, and compressibility are accurately incorporated into the design (Fellenius, 2008). The integration of GEO5 in this study exposed students to professional design methodologies, enabling them to compare hand calculations and spreadsheet models with industry-standard software outputs. This experience reinforced their understanding of geotechnical principles while demonstrating the benefits of computational tools in modern engineering practice.

By combining manual calculations, Excel spreadsheets, and software tools, students developed a well-rounded knowledge of soil behaviour and geotechnical design principles, preparing them for academic and professional applications. The cross-validation of different calculation methods ensured that students understood the governing equations and gained insight into the advantages and limitations of software applications in geotechnical engineering.

3 Methodology

3.1 Course context

This paper investigated the effectiveness of integrating a comprehensive geotechnical site investigation with practical retaining wall design to enhance geotechnical engineering education. This retaining wall design project was conducted as part of the *Geotechnical Engineering* course, which is a six-month module offered in the B.Eng.Tech.Hons programme at the Central University of Technology, Free State. The course builds on foundational knowledge from two preceding six-month courses, *Geotechnical Engineering 1* and *Geotechnical Engineering 2*, which are part of the B.Eng.Tech programme and presented in the second and third years, respectively. These earlier courses provide students with essential geotechnical principles and practical skills that prepare them for the honours-level project. The second and third-year courses typically have between 70 and 90 students enrolled, while the honours course is more specialised, with only 25 students registered in 2024. This smaller cohort size reflects the trend of many students entering the workforce after completing the B.Eng.Tech degree before pursuing honours studies. The project thus serves as an advanced, integrative learning experience designed to deepen students' practical and theoretical understanding of geotechnical design methods in a real-world context.

The methodology centred on a design project where students conducted a detailed site investigation to inform the design of a 3.5-metre-high retaining wall for a road shoulder. The initial phase involved a desktop study for thorough site characterisation, including geographic location, dimensions, current land use, notable features (topography, vegetation, existing structures), and a review of the site's history regarding previous ownership, land use changes, and potential environmental concerns. Students then conducted a field investigation, employing methods such as soil sampling, boring, and in-situ testing to observe soil types and conditions, groundwater levels, and signs of instability, all documented with photographs and diagrams. Soil samples underwent laboratory testing to determine classification properties (grain size distribution, Atterberg limits), shear strength parameters, and compaction characteristics. These results informed the selection of a cantilever retaining wall for its material efficiency, constructed using 30/19 grade concrete and Grade 450 high-tensile steel reinforcement. The design process adhered to South African standards, specifically SANS 10160 for structural loading, including earth pressures and traffic surcharges, and SANS 207 for geotechnical design. Students applied these standards to the design, calculating wall thickness, foundation dimensions, and reinforcement requirements while considering sliding, overturning, and bearing capacity stability factors. The project emphasised the integration of hand calculations and organised Excel spreadsheets to enable precise calculation formulas, generate comprehensive bending schedules, and ensure a professional presentation of results. To validate the accuracy and reliability of these calculations, the results were compared with outputs from the GEO5 software application. This comparative approach allowed for cross-verification of manual and automated computations, enhancing confidence in the design process. By incorporating GEO5, the study ensured consistency with industry-standard geotechnical modelling while using hand calculations and spreadsheets to foster a practical understanding of fundamental geotechnical principles and their application in real-world engineering design.

3.2 Instructor Guidance and Support During the Project

Students are encouraged to proactively manage their progress throughout the semester. When groups fall behind schedule or encounter difficulties in calculating or obtaining soil properties and design parameters, they are permitted to schedule additional practical laboratory sessions with the technical assistant responsible for the module. Furthermore, students may arrange follow-up site visits to clarify field conditions or collect supplementary data. Throughout the semester, instructors monitor students' progress and provide formative guidance during tutorials and consultations. This guidance focuses on keeping students "on track" by identifying conceptual or procedural misunderstandings without directly providing solutions or correct answers. This approach encourages independent problem-solving while ensuring that students do not deviate significantly from the project timeline or objectives.

4 Results and discussion

4.1 Site investigation

The geotechnical site investigation was conducted along the R70 roadway near Welkom, Free State, South Africa, to assess subsurface conditions and soil properties influencing road stability. The site, located at coordinates 27°54'37.6"S, 26°44'52.3"E, is a key transport route connecting Hennenman and Welkom, traversing a relatively flat landscape characterised by sparse vegetation and dry grassland. The local climate is semi-arid, with hot summers and dry, cold winters, contributing to seasonal variations in soil moisture content. The investigation occurred during the winter, when minimal rainfall and dry conditions prevailed, which may have affected soil moisture readings.

The R70 roadway is a well-used regional connector, subject to moderate traffic volumes primarily consisting of passenger vehicles and light commercial transport, with occasional heavy trucks. The absence of extensive industrial activities in the vicinity suggests that traffic loads are not excessive, though cumulative effects from long-term vehicular loads may contribute to road surface deterioration. The surrounding area is undeveloped, with adjacent land used for small-scale agriculture and grazing. Nearby landmarks include Benedicto Farms, Bandu Game Lodge, and the residential suburb of Riebeeckstad, indicating a transition from rural to peri-urban land use.

Historically, the site was largely vacant before road construction, with minimal human impact besides light agricultural activities. No significant preexisting structures or industrial developments existed, and the land remained largely undisturbed before road development. Therefore, the soil and subsurface conditions were expected to be in a relatively natural state, unaffected by prior extensive earthworks or infrastructure. However, undulations on the road surface suggested possible underlying soil movement or compaction issues, prompting the need for investigation. The field investigation involved the excavation of two test pits to evaluate the stratification and composition of subsurface layers (Figure 1).



Figure 1. Excavation of testpit 1 (left) and testpit 2 (right)

A Tractor-Loader-Backhoe (TLB) was used to remove the asphalt layer and expose the underlying materials. Test Pit 1 was successfully excavated, revealing a sequence of soil layers, including an asphalt surface, a compacted G5 and G7 material base, an intermediate silty clay layer, and a deeper high-plasticity clay deposit. Test Pit 2 encountered excavation difficulties due to large aggregate stones ranging from 120 mm to 240 mm, which prevented full penetration. This difference in subsurface conditions suggests that the left and right lanes of the roadway may have been constructed with varying material specifications or at different times. No groundwater was observed in either test pit, consistent with the dry climatic conditions and the absence of surface water bodies near the site. The lack of significant moisture variation in the upper soil layers supports the assumption that the site experiences limited subsurface water movement. The roadway showed no signs of surface erosion, though minor undulations and irregularities on the pavement surface indicated possible settlement or subgrade instability.

4.2 Laboratory results

The laboratory testing for the geotechnical investigation focused on sieve analysis (Figure 2), Atterberg limits, soil classification, oedometer settlement, and shear strength parameters to assess the site's suitability for construction. The Atterberg limits indicated low plasticity, with the liquid limit (LL) and plasticity index (PI) values suggesting minimal volume change due to moisture fluctuations. The soil classification results identified the predominant material as silty sand (SM) with an internal friction angle of approximately 28° , classifying it as a low-plasticity, well-draining soil. The oedometer tests revealed that the reworked residual mudrock exhibited a settlement range between 19 mm and 27 mm under a 50 kPa foundation pressure and 29 mm to 41 mm under a 100 kPa load, indicating moderate compressibility. The collapse settlement analysis showed a slight reduction in void ratio and sample height upon saturation, suggesting a mildly collapsible soil structure. The overall findings confirm that while the soil possesses adequate shear strength for foundation support, its compressibility and potential for collapse necessitate site-specific engineering interventions, including proper compaction, moisture control, and reinforced foundations to mitigate settlement risks.

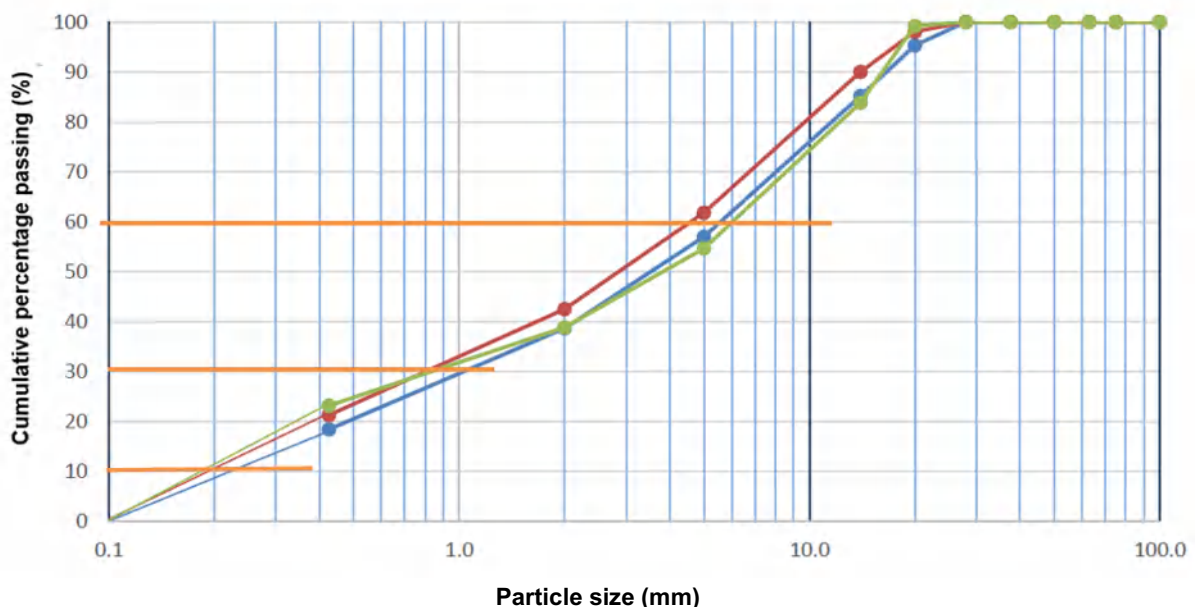


Figure 2. Particle size distribution: testpit 1

Figure 2 presents the particle size distribution (PSD) curves for the three distinct soil horizons encountered in Testpit 1. Each curve shows the cumulative percentage by weight of soil particles finer than a given particle size, plotted on a logarithmic scale from the largest particles on the left to the finest on the right. The three curves correspond to the different soil layers or horizons identified during the site investigation, illustrating the gradation characteristics unique to each horizon. For each curve, key

particle size values- D10, D30, and D60- are indicated. These represent the particle diameters at which 10%, 30%, and 60% of the soil sample's particles are finer by weight, respectively.

4.3 Retaining wall design

4.3.1 Excel spreadsheets

Excel spreadsheets were used to design a retaining wall (Figure 3) by systematically organising design parameters, applying fundamental geotechnical equations, and automating iterative calculations for stability checks. The spreadsheet was structured to input soil properties, wall dimensions, surcharge loads, and groundwater conditions, ensuring flexibility for various design scenarios. Formulas were embedded to calculate the overturning moment by summing the moments of active and passive earth pressures about the wall's toe, allowing for direct computation of the safety factor against overturning. Sliding resistance was assessed by comparing the resisting frictional and passive forces at the wall base to the driving lateral forces, ensuring a sufficient safety factor against sliding failure. The bearing capacity was evaluated by applying both Terzaghi and Meyerhof's bearing capacity equations, integrating soil strength parameters and load distribution to determine the safety factor against foundation failure.

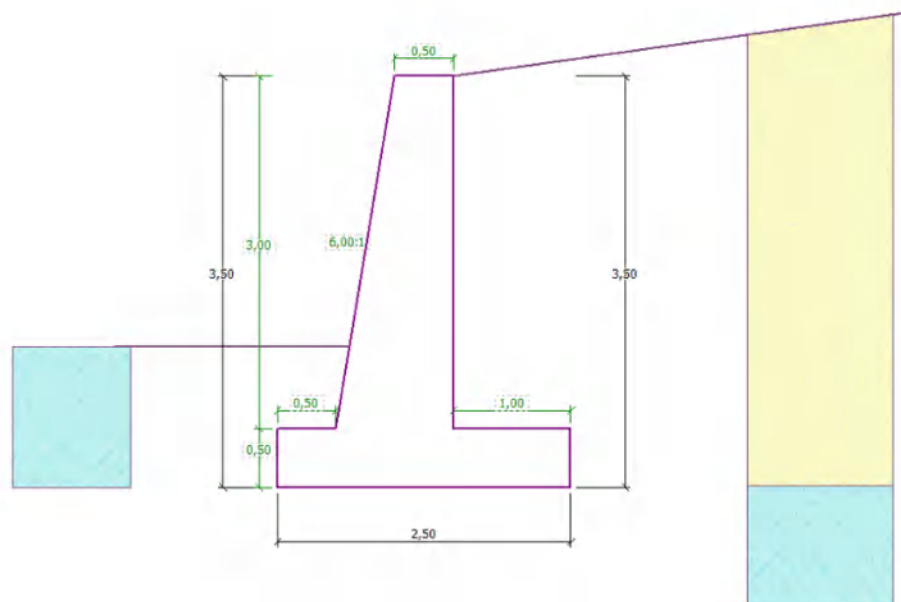


Figure 3. Geometry of retaining wall

4.3.2 GEO5 software

GEO5 software was utilised to design the retaining wall by performing advanced stability analyses, which included overturning, sliding, and bearing capacity assessments based on established geotechnical design methodologies. The software facilitated precise input of soil properties, wall geometry, surcharge loads, and groundwater conditions, automatically generating earth pressure distributions using Rankine theory. GEO5 calculated the moments of driving and resisting forces around the wall's toe for overturning stability and determined the safety factor against toppling failure. The sliding analysis evaluated the horizontal equilibrium between active forces exerted by the retained soil and the resisting forces at the base, considering interface friction and passive resistance. The bearing capacity check employed Terzaghi and Meyerhof's equations to assess foundation stability, ensuring that the applied loads remained within safe limits to prevent excessive settlement or bearing failure. By integrating these calculations into a unified analysis, GEO5 streamlined the design process, provided both graphical and numerical results, and facilitated quick adjustments to optimise wall dimensions and reinforcement. The results were cross-checked with hand calculations and Excel spreadsheets to ensure accuracy and alignment with industry standards.

4.3.3 Comparison

The comparison of the results obtained from the Excel spreadsheet and the GEO5 software package demonstrated a high degree of consistency, with discrepancies limited to decimal variations (Figures 4 & 5). This close alignment validates the accuracy of both approaches, confirming that the manual calculations, structured in Excel, correctly apply fundamental geotechnical principles and stability equations. The minor variations observed are attributed to rounding differences and the inherent numerical precision of GEO5's computational algorithms. The agreement between the two methods reinforces confidence in the reliability of the design calculations, demonstrating that the spreadsheet provides a transparent and adaptable means for preliminary design. At the same time, GEO5 offers an efficient and industry-standard verification tool. This validation process highlights the robustness of the design methodology and ensures that the retaining wall meets safety and performance requirements under different loading conditions.

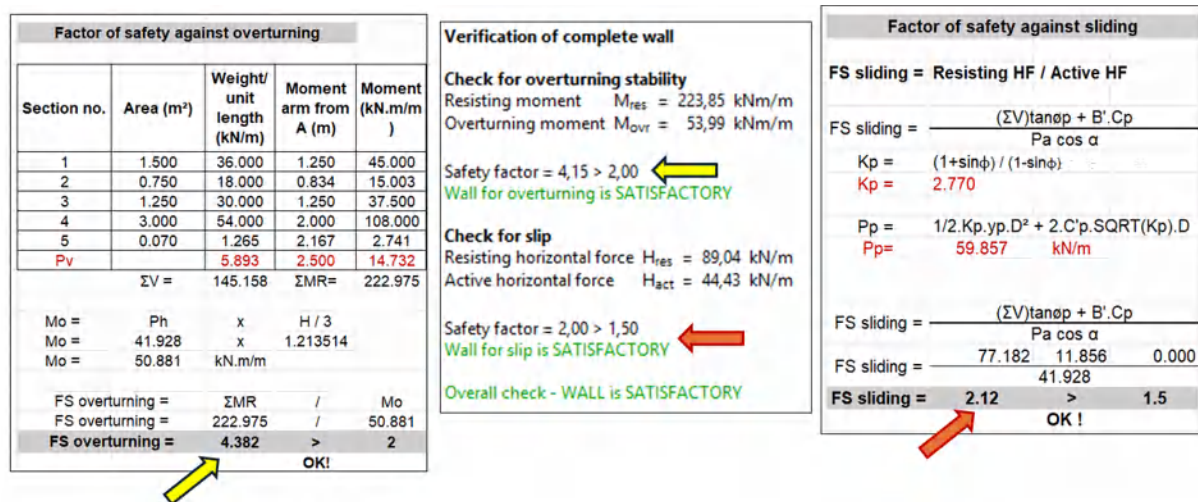


Figure 4. Comparative values between Excel spreadsheet (left & right) and GEO5 software (middle)

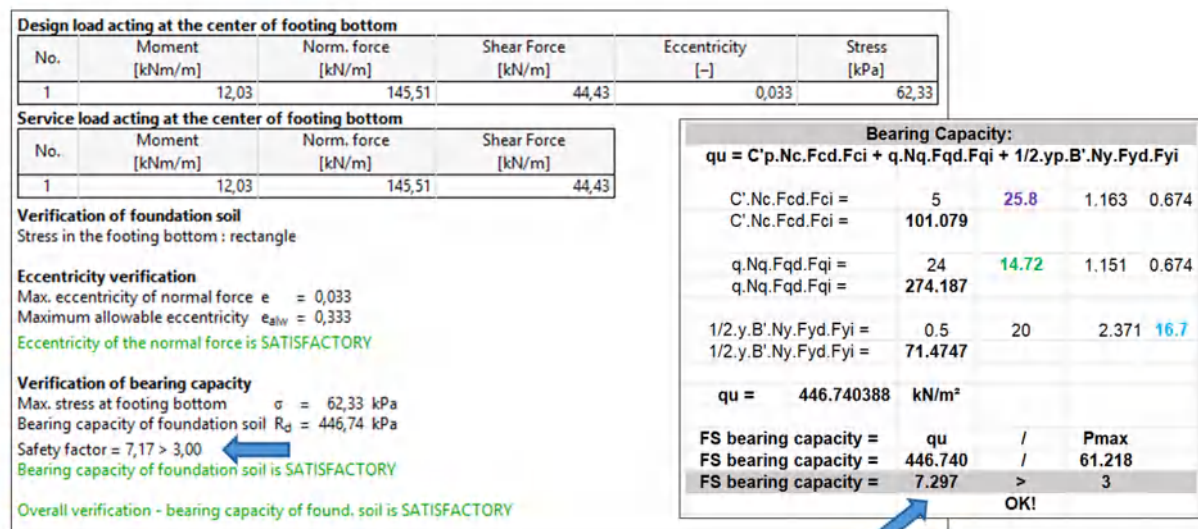


Figure 5. Comparative values between Excel spreadsheet (top) and GEO5 software (bottom)

4.4 Sustaining Practical Learning through Industry Collaboration

Access to active construction sites for in-situ testing and soil sampling is indeed invaluable for geotechnical engineering education. Recognising the challenges in consistently securing such access annually, the Civil Engineering Department at the Central University of Technology maintains ongoing

collaborative projects with industry partners. These projects are real-world engineering challenges with a strong research component, often focusing on aspects that industry partners lack the time or funding to address themselves. Postgraduate students are actively involved in these projects, gaining hands-on experience in field investigations and laboratory testing within authentic industrial contexts. This model not only ensures sustained practical exposure despite potential limitations in site availability but also fosters mutually beneficial relationships between academia and industry. For readers aiming to implement similar programmes, establishing formal partnerships with local engineering firms, contractors, or government agencies can provide continuous access to live projects. Additionally, integrating research-focused elements into these collaborations can attract industry interest by addressing their knowledge gaps, thereby securing long-term engagement and enriching student learning

5 Student Feedback and Comparative Reflection

Formal student evaluations conducted at the end of the module provide evidence of the exercise's positive impact on the students. These evaluations are collected via an anonymous university-wide online survey, where students assess various aspects of their courses, including the lecturer's effectiveness, the module content, and its practical value. Feedback from the 2024 cohort indicated a positive reception to the retaining wall design project, with students highlighting its practical relevance and the integration of fieldwork, laboratory testing, and computational analysis as particularly valuable for their learning experience. Comparatively, in years prior to the inclusion of this comprehensive design project, student feedback reflected a desire for more hands-on and integrative practical exercises within the geotechnical engineering curriculum. The introduction of this project has thus enhanced student engagement and understanding, as evidenced by improved evaluation scores related to the module's applicability and the development of practical skills. This aligns with educational research emphasising the importance of active, problem-based learning in engineering education to improve comprehension and motivation

6 Conclusions

In conclusion, the exercise offered students a comprehensive, hands-on approach to geotechnical design, integrating field investigations, laboratory testing, and computational analysis. The site investigation provided practical experience in soil profiling, sample collection, and in-situ testing, enhancing their understanding of subsurface conditions and retaining wall design. Laboratory tests determined key parameters like soil classification, Atterberg limits, shear strength, and bearing capacity, emphasising their role in structural stability. Students worked in groups of five but were assessed individually through rubrics and detailed reports. They faced challenges due to the project's intensity alongside other coursework within 15 weeks, highlighting the need for careful scheduling to avoid overwhelm. Using Excel and GEO5 software, they developed skills in geotechnical calculations, assessing overturning, sliding, and bearing capacity factors. The spreadsheet approach clarified fundamental equations, while GEO5 introduced industry-standard automated computations. Comparison of both methods showed high consistency, validating their accuracy and the importance of cross-verification. Overall, the assignment enhanced their technical skills, confidence in software and manual calculations, and ability to integrate methodologies and communicate findings, preparing them well for professional geotechnical engineering roles.

References

- Abdel Rahman, A. (2023). Bridging the Gap: The Importance of Practical Training for Engineering Students, ABB News. Available at: <https://new.abb.com/news/detail/107165/bridging-the-gap-the-importance-of-practical-training-for-engineering-students> (Accessed: 14 February 2025).
- Budhu, M. (2015). Soil Mechanics Fundamentals. Metric version. Chichester: Wiley-Blackwell.
- Coduto, D.P. (2001). Foundation Design: Principles and Practices. 2nd ed. Upper Saddle River, NJ: Prentice Hall.

- Das, B.M. (2010). Principles of Geotechnical Engineering. 7th ed. Stamford: Cengage Learning.
- Day, P. (2015). The Role of Soil Properties in Foundation Design. International Journal of Geotechnical Engineering, 9(4), pp. 309-317. doi:10.1080/19386362.2015.1048857.
- Diwalkar, A. (2020). Analysis and Design of Retaining Wall: A Review. 2nd International Conference on Communication & Information Processing (ICCIP) 2020. Available at SSRN: <https://ssrn.com/abstract=3648731> or <http://dx.doi.org/10.2139/ssrn.3648731>.
- Douglas Partners (2024). 'What is a geotechnical investigation?' Available at: <https://www.douglaspartners.com.au/geotechnical-investigation> (Accessed: 14 February 2025).
- Eliot Sinclair (2024). 'The importance of geotechnical site investigations'. Available at: <https://www.eliot Sinclair.co.nz/geotechnical-site-investigations/> (Accessed: 14 February 2025).
- Ferguson, G., Kwan, C. (2021a). Engineering education: Bridging the gap between theory and practice. Journal of Engineering Education, 110(3), pp. 345-362.
- Ferguson, G., Kwan, C. (2021b). Understanding Soil Consolidation: The Role of the Oedometer Test. Journal of Soil Mechanics, 15(4), pp. 201-215.
- GEO5 (2024). GEO5: Geotechnical Software for Civil Engineers. Available at: <https://www.finesoftware.eu/geotechnical-software/> (Accessed: 14 February 2025).
- Keller, T., Dexter, A.R. (2019). Determination of shear strength parameters using the triaxial test. Geotechnical Testing Journal, 42(4), pp. 1-10.
- Keller, T., Dexter, A.R. (2020). Determination of shear strength parameters using the triaxial test. Geotechnical Testing Journal, 43(5), pp. 123-135.
- Moore, D. (2012). Using Excel spreadsheets to enhance learning in geotechnical engineering. Proceedings of the 15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, pp. 1-8. Available at: <https://www.issmge.org/uploads/publications/3/5/CH025.pdf> (Accessed: 14 February 2025).
- OzGeos (2024). Geotechnical investigations for construction projects. Available at: <https://www.ozgeos.com.au/geotechnical-investigations/> (Accessed: 14 February 2025).
- Nawaz, M.N., Qamar, S.U., Alshameri, B., Nawaz, M.N., Hassan, W., Awan T.A. (2022). A robust prediction model for evaluation of plastic limit based on sieve # 200 passing material using gene expression programming. PLoS One. 17(10):e0275524.
- Rocscience (2024). Geotechnical Software for Analysis and Design. Available at: <https://www.rocscience.com> (Accessed: 14 February 2025).
- Shrawankar, G. K., Gangwal, S. (2024). Review on Design and Sustainability of Retaining Wall Structures. International Journal of Scientific Research & Engineering Trends, 10(1), 97-107.
- Smith, J., Jones, A. (2023). 'The influence of soil suction on lateral earth pressure against retaining walls', Journal of Geotechnical Engineering, 149(5), pp. 1-10.
- Toll, D. G. (2001). Modelling unsaturated soil behaviour. Geotechnical Engineering, 149(4), pp. 167-179.
- UTA. (2024). Atterberg limit test – properties and behavior of soil. Available at: <https://uta.pressbooks.pub/soilmechanics/chapter/atterberg-limit-test/> (Accessed: 14 February 2025)

Authors' bios

Elizabeth Theron, University of Technology, Free State (South Africa)

Elizabeth Theron has over 35 years of academic experience, strongly focusing on geotechnical engineering. She has developed innovative teaching materials and methodologies, significantly enhancing student learning experiences. Her research, particularly on foundation problems related to heaving clays, has earned her multiple awards, including the J.E. Jennings Award from the South African Institution of Civil Engineering for three consecutive years (2017-2019). In addition to her academic roles, she actively participates in community projects, such as the Pothole Eradication Programme, demonstrating her commitment to applying engineering solutions to real-world challenges. She maintains high professional standards as a registered Professional Engineering Technologist with the Engineering Council of South Africa.

Jonathan D Steenkamp, University of Technology, Free State (South Africa)

Jonathan Steenkamp is a technical lecturer at the Central University of Technology, South Africa. He holds a National Diploma, Advanced Diploma, and a Bachelor of Engineering Technology Honours degree in Civil Engineering from the same institution. Currently, he is pursuing a Master of Engineering degree with a research focus on the rehabilitation of gravel roads using nanotechnology. He has 14 years of industry experience in construction management and five years in academia. He specialises in teaching geotechnical engineering. In addition to his academic role, he serves as the project coordinator for the Pothole Eradication Project, an initiative dedicated to community upliftment and the skills development of unemployed youth in the Free State region. He is also a member of the South African Institute of Civil Engineering and is registered as a Candidate Technologist with the Engineering Council of South Africa.

Samuel G Waters, University of Technology, Free State (South Africa)

Samuel Waters is a lecturer in Geomatics and Engineering Surveying at the Central University of Technology, Bloemfontein, with seven years of academic experience. He also teaches the final-year Project subject, integrating practical applications with theoretical knowledge. His research focuses on database design, problematic soil identification, road inspection, and Geographic Information Systems (GIS). He has contributed to the field through publications and conference presentations, with his work recognised by the National Research Foundation of South Africa, which awarded him a Thuthuka Research Grant for 2025. Samuel is committed to advancing geospatial and geotechnical methodologies, particularly in South Africa's diverse soil and infrastructure environments.

Paul Vosloo, University of Technology, Free State (South Africa)

Paul Vosloo is a lecturer at the Central University of Technology in Bloemfontein, South Africa, specialising in structural design and geotechnical engineering. With a decade of industry experience in civil and structural engineering, he brings practical insights to his academic role. His research focuses on soil variability, suction, shear strength, and soil-water characteristic curves, which are crucial for understanding unsaturated soil behaviour. Paul has contributed to the field through publications and presentations, and his work has been recognised by the National Research Foundation of South Africa, which awarded him a Thuthuka Research Grant for 2025. He is committed to advancing geotechnical engineering through teaching and research to bridge the gap between theoretical concepts and practical applications.

Open Resource Educational Material

Development of shareable activity library for geoenvironmental engineering education

G. Bohnhoff¹, K. Sample-Lord², J. Hubler², N. Strandberg³ & J. Walleser³

¹*Milwaukee School of Engineering, Milwaukee, WI United States*
bohnhoff@msoe.edu

²*Villanova University, Villanova, PA United States*
kristin.sample-lord@villanova.edu, jonathan.hubler@villanova.edu

³*University of Wisconsin-Platteville, Platteville, WI United States*
strandberg@uwplatt.edu, walleserj@uwplatt.edu

ABSTRACT: Active learning has been shown to increase student engagement, performance, and retention. Thus, active learning techniques have seen exponentially increasing adoption in engineering education as methods to inspire and challenge students, as well as emphasize relationships between technical content and real-world applications. Sharing of active learning resources that can be easily adapted and implemented by others can help faculty become more effective educators. Although collections of shareable activities for use in geotechnical engineering courses exist, such resources for geoenvironmental engineering topics are more limited. This paper describes an ongoing multi-year project to create, implement, and disseminate a shareable activity library for geoenvironmental engineering education. The project is a collaborative effort between teams at three U.S. institutions, with the goal of creating a digital library of geoenvironmental educational activities that promote active learning in the classroom and are easy for faculty to implement. A detailed example of an activity in the library is shared in the paper. The example is a hands-on, competitive group activity designed to teach students about flow and water quality through experiential learning. The instructor notes, student handout, materials list, and photographs are provided to allow the reader to easily implement the activity in their own course or event.

Keywords: Geoenvironmental engineering, Activity library, Active learning

1 Introduction

Active learning has been shown to increase student engagement, performance, and retention (Schultz et al., 2010). Thus, active learning techniques have seen exponentially increasing adoption in civil engineering education as methods to inspire and challenge students, as well as emphasize relationships between technical content and real-world infrastructure. In order to attract students to the field of geotechnical engineering, we need to create an awareness and interest in the field, so students consider geotechnical engineering as an option for their future careers. To "sell" geotechnical engineering to students at all levels (K-12, undergraduate, graduate), outreach activities and course materials should be engaging, relevant, interesting, and challenging (Townsend, 2005; Wirth et al., 2017). However, the time required to create active learning curriculum can be prohibitive, especially for new faculty members. Sharing of active learning resources that can be easily adapted and immediately implemented by others (e.g., digital activity library) can assist faculty to become more effective educators, with the ultimate goal of improving student learning and increasing participation in STEM fields.

The authors previously developed and disseminated a digital activity library, similar to the project

described herein, for geotechnical topics in a typical undergraduate soil mechanics course. That work was supported through a Special Project grant from the United States Universities Council on Geotechnical Education and Research (USUCGER). Undergraduate and graduate researchers at Villanova and UW-Platteville collaborated to develop 16 classroom activities. The implementation of the activities showed improvement in students' perceptions of overall student learning and engagement. In addition, students reported increased interest in geotechnical engineering, and felt the activities provided real-world context (Bohnhoff and Sample-Lord, 2019). The library is freely available on the USUCGER webpage and was disseminated at the NSF-funded Geotechnical Faculty Teaching Strategies Workshop co-organized by the authors in 2020. The positive response the authors have received from the geotechnical community regarding this soil mechanics activity library motivated the development of an activity library for geoenvironmental courses, which is the topic of this paper.

Development of the new geoenvironmental activity library represents a multi-year, collaborative effort between Villanova University, University of Wisconsin-Platteville, and Milwaukee School of Engineering. The project began in 2022, and completion and public dissemination of the library is expected in 2027. So far, multiple activities have been developed and piloted in geotechnical engineering courses and engineering outreach events. This paper describes the goals and approaches guiding the library development, plans for sharing the resource with the geotechnical and geoenvironmental engineering community, and a detailed example of one of the activities that has already been implemented. The example is a hands-on, competitive group activity designed to teach students about flow and water quality through experiential learning. This activity was developed with the help of two undergraduate assistants and then successfully implemented at an outreach event for students ages 15-17 and a junior-level soil mechanics laboratory. The instructor notes, student handout, materials list, and photographs are provided to allow the reader to easily implement the activity in their own course or event.

2 Background

2.1 Active and Experiential Learning

Active learning involves the student in the learning process and may increase student interest and retention (Schultz et al., 2010). Active learning often involves groups and provides the opportunity for students to interact with their classmates, learn problem solving techniques, and participate on teams in non-stressful situations. In addition, small groups allow time for instructors to circulate around and provide feedback and instructions (Sternberg, 1997; Murzi, 2014). Active learning provides an opportunity to connect course materials with real-world infrastructure. Active learning in this paper refers to learning that occurs through performing interactive in-class activities.

Experiential learning, or learning by doing and reflection, is a form of active learning where students learn fundamental concepts through doing and observation. Thus, detailed prior knowledge on a concept is not required. The hands-on form of experiential learning follows the “see it, do it, learn it” model as depicted in Figure 1. Students participate in an adventure or challenge carefully crafted by instructors. After completing the challenge, students are guided through observation and reflection. The observation and reflection help students form ideas and theories based on their experiences and connect these experiences to “real-world” experiences (AEE, 2025; Kolb, 1984). This process of learn-by-doing and reflecting enhances student interest in science and engineering because they can see links between topic and everyday lives (Artis & Washington, 2021). In addition, experiential learning is used in outreach to increase interest in STEM careers – these outreach activities show students how rewarding, enjoyable and beneficial engineering careers can be (Williams et al., 2019).

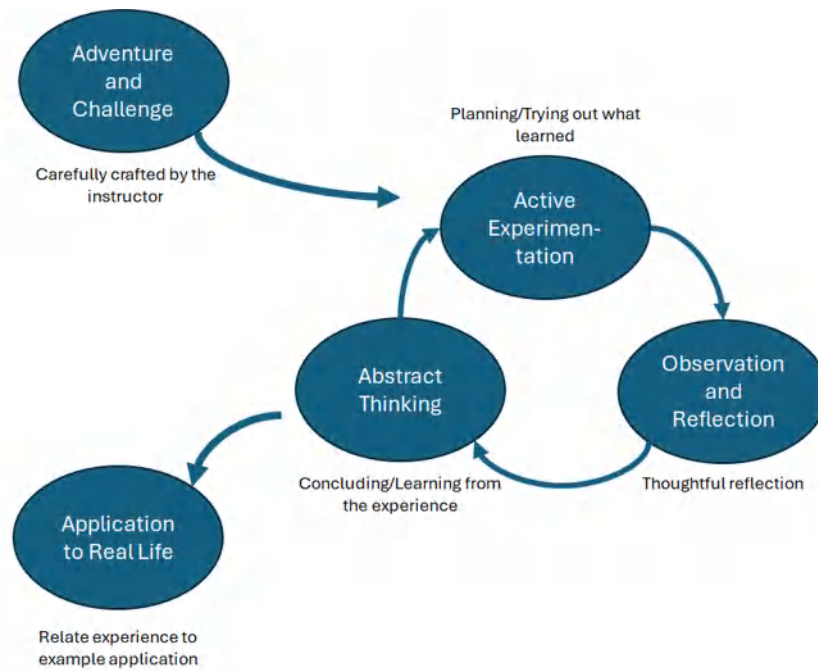


Figure 1. The experiential learning cycle (modified after Kolb, 1984).

2.2 Existing Resources and Approaches

The goal of this project is to create a geoenvironmental engineering activity library with shareable resources that are easy to implement. The activities will be designed to be transferable and suitable for use in both undergraduate engineering courses (e.g., Soil Mechanics) and STEM outreach events (students ages 14-18). Upon completion, the developed library will include 12-15 activities on a range of geoenvironmental topics. The activities will range in duration (5 – 60 min), student group size (2-5 students), and formats (e.g., competition, jigsaws) to allow for flexibility in implementation, available resources, and target audience. Provided resources will include detailed instructor notes and objectives, student handouts, videos and/or photos. Upon completion, the library will be available as a downloadable file and disseminated through the geoenvironmental and geotechnical engineering communities (e.g., USUCGER, ISSMGE TC306).

This geoenvironmental activity library will be similar to one created by the authors Sample-Lord and Bohnhoff for use in soil mechanics courses created through a grant supported by USUCGER (Sample-Lord and Bohnhoff, 2017; Bohnhoff and Sample-Lord 2019). In order for the Soil Mechanics Activity library to be useful for geotechnical faculty members, the materials were created so that faculty members could “grab-and-go” and implement the activity of choice in their class. Teaching materials and supplemental information were provided in pdf and Microsoft Word, Excel, and PowerPoint file formats to allow for instructor editing. All activities were piloted in undergraduate classes before being finalized and peer reviewed by four USUCGER members with experience teaching undergraduate geotechnical courses at a range of institutions.

The authors modelled their efforts after using the extensive materials available through the Science Education Resource Center (SERC) at Carleton College for their geoscience courses. SERC had origins in the geoscience community but has expanded across the STEM disciplines. SERC has an extensive collection of pedagogical resources. Each teaching activity in the SERC library includes a short summary, provides context (e.g., audience, required skills, activity length), goals or learning objectives, description of teaching materials, teaching notes and tips, information on assessment, and references and resources. The activities available in the SERC database are reviewed with a comprehensive rubric ([Activity Review Rubric](#)) based on five main elements including: scientific veracity; alignment of goals, activity, and assessment; pedagogical effectiveness; robustness (usability and dependability of all lesson components); and completeness. Each of the reviewed activities is given one of four ratings: Exemplary, Reviewed, Activity Idea, or Deaccession. The deaccession rated activities contain serious deficiencies and are removed from the collection ([Activity Review](#)).

In addition to the teaching materials created by Sample-Lord and Bohnhoff (2017) and those available on the SERC website, there is a variety of geotechnical engineering resources available, albeit, with varying degrees of peer review and oversight. A partial list of these shareable resources is included in Table 1. There are additional international resources, and a broad range of YouTube channels dedicated to geotechnical engineering education that are not included in this list. As can be seen in Table 1, collections of shareable activities for use in geotechnical engineering courses exist. However, such resources for geoenvironmental engineering topics are more limited.

Table 1. Partial list of geotechnical engineering teaching resources

Resource	Location	Description of resources
United States Universities Council on Geotechnical Education and Research (USUCGER) Teaching Aids	https://usucger.org/teaching-aids/	Summary of Teaching Resources, Free Recorded Lectures, Photo Resources, and Software compiled by the USUCGER community
Case Western Database	https://engineering.case.edu/geodatabase	Database of over 234 tests conducted on three different sands for the validation of dynamic and static constitutive relations
Center for Bio-mediated and Bio-inspired Geotechnics (CBBG) Biogeotechnical Engineering Curriculum	https://cbbg.engineering.asu.edu/education/curriculum/	Collection of teaching modules, lesson plans and resources for the Pre-college level, University level, Practitioner level, and Outreach Demonstrations
Science Education Resource Center (SERC) at Carleton College	https://serc.carleton.edu/index.html	One of the world's largest collections of pedagogical resources for the geosciences and STEM education
Geoengineer	https://www.geoengineer.org/education	Assorted resources on a variety of geoengineering topics
National Center for Case Study Teaching in Science (NCCSTS) Case Collection	https://www.nsta.org/case-studies/all	Compilation of studies. Some case studies (especially one on sinkholes) related to geotechnical engineering and geology – requires a membership fee for access to solutions
International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) Education Resources	https://www.issmge.org/education/Virtual University https://www.issmge.org/education/virtual-university Videotaped Honour Lectures https://www.issmge.org/education/videotaped-honor-lectures Recorded Webinars https://www.issmge.org/education/recorded-webinars Presentations https://www.issmge.org/education/presentations Peer-reviewed Educational Materials https://www.issmge.org/education/peer-reviewed-educational-materials	Collection of resources including Virtual University, Honour Lectures, Recorded Webinars, Presentations, and Peer-Reviewed Educational Materials

Note: This is a partial list mostly limited to US-based resources. Additional international resources may be available but are not included in this list.

3 Activity Library

3.1 Goals and Criteria for Library Development

The goal is to create a digital library of geoenvironmental educational activities that promote active learning in the classroom and are easy for faculty to implement in their own courses with little to no preparation. Work on the geoenvironmental activity library began in 2022, and the completed library is expected to include 12-15 activities for incorporation in undergraduate and graduate geotechnical, environmental, and geoenvironmental courses. Components of the activities are also being designed to be suitable for use as STEM activities for middle and high school students. The following criteria are being applied in the development of the library: (1) the final product must be a useful resource for engineering educators; (2) the primary purpose of all activities must be to enhance student learning; (3) the collection of activities are for a range of in-class times (5 – 50 minutes) to allow flexibility in implementation in existing courses; (4) the activities are for a range of small group sizes (2 – 5 students) to allow for use in a range of class sizes; (5) the activities are for a range of formats (e.g., quantitative problems, jigsaws, concept questions), to allow for different room types, student backgrounds, and teaching methods; and (6) the work provides a valuable learning experience for the undergraduate assistants helping the authors with organizing and developing the materials.

3.2 Materials and Topics Included in the Library

Materials for each activity include digital versions (Word/PDF/Excel/MP4) of: (1) a summary sheet for the instructor with learning objectives and instructions; (2) activity handout; (3) solution set; (4) example rubric; and (5) a short video (if applicable). The short videos (1 – 5 minutes) include demonstrations by the undergraduate assistants, mini lectures, or case studies. Since the purpose of the library is for educators to "grab-and-go" the activity of their choice and use the materials immediately, the library (once completed) will be publicly available as a downloadable zip file from the USUCGER Teaching Aids website.

The activities in the library focus on the following main themes:

- Fluid flow and contaminant fate and transport in porous media, geochemistry, and clay behavior for geoenvironmental applications
- Regulations and standards relevant to geoenvironmental engineering
- Remediation and monitoring of contaminated soils and groundwater
- Types of waste in geoenvironmental containment applications (mining, landfills, radioactive, sediments, etc.)
- Engineered barriers (geomembranes, clay liners, vertical cutoff walls, permeable reactive barriers, landfill caps/covers)
- Waste reuse / recycled materials

4 Example Activity

4.1 Context and Objectives for Example Activity

An example is provided herein for an activity focused on fluid flow through porous media layers and impacts on water quality. The activity is intentionally designed to be adaptable for use with:

- 1) High school and middle school students (grades 6-12) that have no prior knowledge of soil mechanics or flow in porous media.
- 2) Undergraduate students in an introductory soil mechanics course who have not yet learned the related fundamentals (Darcy's Law, hydraulic conductivity, geosynthetics, etc.)

This is an experiential learning activity. The intent is for students to learn fundamental concepts through doing and observation (hands-on trial and error), **without being taught any of the underlying technical concepts beforehand**. After the experience, the instructor uses the students' own observations to then begin to teach the technical concepts (i.e., let's discuss "why" that happened). Thus, the activity can be deployed at any stage of education (grades 6-12, or any undergraduate level), as no prior knowledge is required for the students to participate.

The intended takeaway messages for middle and high school students are that: (1) soils and geosynthetics are important engineering materials; and (2) often in engineering you are trying to achieve multiple (and sometimes competing) design criteria. The learning objectives for university students are:

- 1) Construct a system with layers of different geo-materials that meets design criteria for minimum flow rate and water quality improvement. [Bloom's level: Create]
- 2) Compare the relative permeability of different geo-materials based on flow rate observations. [Bloom's level: Evaluate]
- 3) Assess the effectiveness of different geo-materials for filtering sediment from "dirty water" based on visual observations of water quality. [Bloom's level: Evaluate]

4.2 Materials and Resources Required for Example Activity

The activity was designed to utilize materials that are available in most soils laboratories, or can be obtained with minimal cost. Students are separated into groups, with a recommended size of three to six students per group. Each group is provided a set of materials as shown in Figure 2. The materials include:

- 250 mL graduated cylinder
- Plastic soda bottle (12 oz (354 mL) to 17 oz (502 mL)) cut into two pieces, as shown in Figure 2
 - Cut off the rounded top half of the bottle and flip over, to use as a funnel for the flow (see image, on top of graduated cylinder)
 - Poke 4-6 small holes in the base of the bottom half of the bottle. The bottom half of the bottle will be filled with the layers of each material, and flow will exit through the holes at the bottom.
 - The exact size of the soda bottle does not matter, as long as it is consistent between groups.
- Pieces of geosynthetics or fabric, pre-cut to the inner diameter of the bottle
 - In the example in Figure 2, there are two geotextiles shown (2 pieces each). If using geosynthetics or fabric, at least one should be suitable for filter applications. The second material can be similar, or very different (such as geomembrane for containment, as the intent is to also have materials that do not work well for the design goals). You may use other materials instead that you have more easily on hand, such as felt fabric, coffee filters, etc.
- Bowls of different soil sizes, ranging from clay to coarse sand/gravel
 - In Figure 2, there is a bowl of bentonite clay, fine sand, medium sand, and gravel. However, you may use any materials you have as long as there is some finer and coarser material.
- 150 mL of "dirty water", per design trial
 - Prepare a large bucket of "dirty water" beforehand by mixing tap water and soil passing the #200 sieve. For each design trial, mix up the bucket well and re-fill a cup/beaker with 150 mL for each group.
- Paper towels

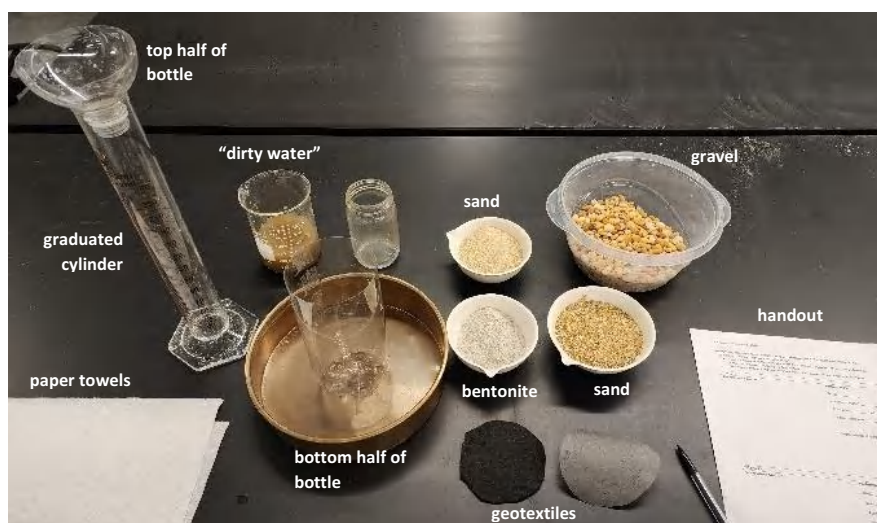


Figure 2. Materials provided to each group for the example activity.

Most students preferred to use the stopwatch on their phone or computer (rather than a handheld stopwatch). Other necessary equipment to have in the room includes a bucket to dump the “old designs” into (mix of soil and geotextile), paper towels, and a large jug of the “dirty water” supply (tap water pre-mixed with soil passing the #200 sieve).

4.3 Instructions for Leading Example Activity

The following timeline has been used successfully for this activity for a one-hour long class or event:

- Prior to day of activity: Gather/prepare materials
- 15 minutes before activity: Setup materials at each station. Remix the “dirty water”.
- 0:00 – 0:05 min: Break students into groups. Give handout (Figure 3).
- 0:05 – 0:10 min: Introduce activity
 - Say a range of geomaterials has been provided, but don’t describe what they are.
 - Explain the goal is to use the materials by placing them in layers in the perforated bottle to meet the design criteria → See the handout for criteria.
 - This is a competition to achieve the best water quality (based on visual comparison by the instructor). But if there is a tie for best water quality, the one with the faster flow rate will win.
- 0:15 – 0:45 min: Trial tests and redesigns (stay at own tables)
 - Students make first design. Make sure not to give hints or say what the materials are. Encourage students to discuss design decisions before constructing, but don’t wait too long to try something. Draw sketch on handout and construct layers in bottom half of bottle.
 - When they are ready for a trial test – tell instructor you are ready. Place filled bottle on top of the cut bottle top and graduated cylinder. Instructor mixes and pours 150 mL of dirty water into the bottle, and students start timer. When water flow slows / stops, stop the timers. Record the time and the collected water volume on the handout. Check that flow rate above the minimum criteria. Students visually compare their collected water to original “dirty water” to observe whether quality improved (with clear water being of the highest quality).
 - Students keep a sample of their water in the jar to use for comparison with next trial.
 - Redesign: Students dump used materials and collected water in waste bucket, and wipe out bottle with paper towels. Obtain more materials if needed. Setup new design. Draw sketch. Run another trial.
 - Repeat redesigns. Most groups will try about three total designs.
 - Once within 10 minutes of competition time, construct final design. Clean graduated cylinder.
- 0:45 – 0:50 min: Competition
 - Students bring filled bottle, cylinder, and 150 mL of dirty water to the competition table. Setup MUST BE on the competition table by 0:50 min or they are disqualified (like a baking show competition). Bottle with materials should be on the table (not on collection cylinder yet).
 - When instructed, the groups put their bottle on top of their cylinder and they pour in dirty water (e.g., when instructor says “go”).
 - At least 2 students should be in charge of timing for each setup. Timers also start at “go”. Groups record the time when they reach 20 mL.
 - Confirm each group met the minimum flow rate, otherwise they are disqualified. (Hint: If they reach 20 mL and it’s not 5 minutes yet, you know they are fine.)
 - Put cylinders side by side to compare for best water quality. If you cannot tell the difference between the best ones, then the winner will be based on best water quality *and* fastest rate.
 - Declare winner.
- 0:50 min – 1:00 hr: Reflection and segue
 - First ask students what they observed about the different materials (e.g., flow rates, water retention, filtering). Then tell them what the materials were.
 - Relate to example engineering applications (e.g., when is drainage versus filtering important).
 - Conclude (e.g., what topics they will learn in lecture next time that will explain what they observed today).

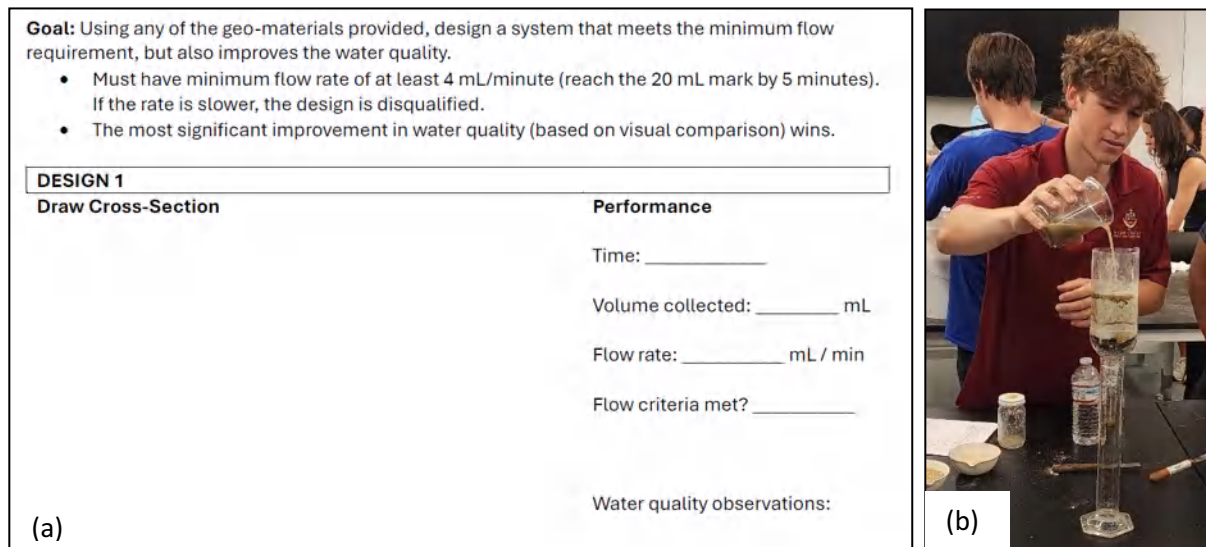


Figure 3. (a) Handout for activity. Additional sections (e.g., Design 2) can be added for multiple iterations. (b) Example trial test.

5 Plans for Assessment and Feedback

Completion and public dissemination of the library is expected in 2027. Early activities have been developed and piloted in geotechnical engineering courses and engineering outreach events, to obtain preliminary feedback for refinement. Initial feedback and refinements have focused primarily on logistics and clarity of materials. The next phase of assessment will include piloting additional activities in geotechnical courses and outreach activities at MSOE and Villanova, peer review by geoenvironmental faculty members using a rubric similar to that used by the SERC community, and surveys for collecting student feedback. After dissemination, faculty that implement the materials will be asked to complete a survey to provide feedback about the materials and faculty and student experiences at other institutions.

6 Summary

A shareable geoenvironmental engineering activity library is being developed through a multi-year collaborative effort between Villanova University, University of Wisconsin-Platteville, and Milwaukee School of Engineering (MSOE). Development of the library began in 2022 and completion and dissemination are expected in 2027. The goal of the activity library is to promote active learning in the classroom and help faculty become more effective educators. The library will include shareable resources that are easy for faculty to implement in their own courses with little to no preparation. The final library will include 12-15 activities for incorporation in undergraduate and graduate geotechnical, environmental, and geoenvironmental courses. Some activities are also suitable for use as STEM activities for middle school and high school students. This paper describes a detailed example of one of the activities that has already been implemented. This hands-on, competitive group activity was designed to teach students about flow and water quality through experiential learning. This example activity was implemented at an outreach event for students ages 15-17 and also a junior level soil mechanics course. The materials needed to implement this example activity in an outreach event or in an undergraduate course are provided in this paper.

Acknowledgements

Financial support for this project is provided by the U.S. National Science Foundation (NSF), Arlington, VA under Grant No. CMMI-2143145. The opinions expressed in this paper are solely those of the authors and are not necessarily consistent with the policies or opinions of the NSF.

References

- Association for Experiential Education (AEE) (2025). "LTE – Experiential Education." <https://www.aee.org/what-is-experiential-education> (Jan. 30, 2025).
- Artis, S., Washington, G. N. (2021). See It, Do It, Learn It: Integrating Experiential Learning into High School Engineering Outreach Programs Paper presented at 2021 CoNECD, Virtual. 10.18260/1-2—36119
- Bohnhoff, G.L., Sample-Lord, K. M. (2019). *Creating a Library of Group Activities that Promote Active Learning in the Undergraduate Soil Mechanics Classroom*. Proceedings of the 2019 ASEE Annual Conference & Exposition, Tampa, Florida. 10.18260/1-2—32557
- Kershaw, K., Luna, R., Carroll, J. C., Lovell, M. D., Derks, A. C. (2021). Design and Implementation of Experiential Learning Modules for Geotechnical Engineering Paper presented at 2021 ASEE Virtual Annual Conference Content Access, Virtual Conference. 10.18260/1-2—36909
- Kolb, D. A. (1984). *Experiential learning: Experience as the source of learning and development*. Englewood Cliffs, NJ: Prentice-Hall.
- Murzi, H. G. (2014). Team-Based Learning Theory Applied to Engineering Education: A Systematic Review of Literature. in Proceedings of the American Society of Engineering Education Annual Conference & Exposition, Indianapolis, IN, June 15-18, 2014.
- Sample-Lord, K.M., Bohnhoff, G.L. (2017). Final Report: Creation of a library of group activities that promote active learning in the undergraduate soil mechanics classroom. 2016-2017 Special Grants Program, United States Universities Council on Geotechnical Education and Research (USUCGER).
- Schultz, J., Wilson, J., Hess, K. (2010). Team-based classroom pedagogy reframed: the student perspective. *American Journal of Business Education*, 3(7), pp. 17-24.
- Sternberg, S.P. (1997). Small Group, In Class Problem Solving Exercises. in Proceeding of the American Society of Engineering Education 1997 Annual Conference, Milwaukee, WI, USA, June 15 -18, 1997.
- Townsend, F. (2005). Challenges for geotechnical engineering graduate education. *J. Prof. Issues Eng. Educ. Pract.*, 10.1061/(ASCE)1052-3928(2005)131:3(163), 163–16.
- Williams, R., Frizell, S., Nave, F., Thompson, A. (2019). Using Experiential and Collaborative Learning to promote Careers in Engineering Paper presented at 2018 Gulf Southwest Section Conference, AT&T Executive Education and Conference Center, Austin, TX 78705. 10.18260/1-2-370.620-31563
- Wirth, X., Jiang, N.-J., da Silva, T., Della Vecchia, G., Evans, J., Romero, E., Bhatia, S.K. (2017) Undergraduate geotechnical engineering education of the 21st century. *J. Prof. Eng., Educ. Pract.* 143(3): 02516002.

Authors' bios

Gretchen Bohnhoff, Milwaukee School of Engineering (USA)

Dr. Gretchen Bohnhoff is a professor in the Civil & Architectural Engineering and Construction Management Department at the Milwaukee School of Engineering (MSOE). MSOE is a primarily undergraduate institution in Milwaukee, Wisconsin with ~400 undergraduate civil, and architectural engineering, and construction management students. Dr. Bohnhoff earned her PhD in Civil Engineering with an emphasis in Geoenvironmental Engineering from Colorado State University, and both her Master

of Science in Geological Engineering and Bachelor of Science in Geological Engineering and Geology from the University of Wisconsin-Madison. Dr. Bohnhoff's teaching and research focuses on the intersection of environmental engineering, geotechnical engineering, and groundwater engineering. Her research has a common theme of sustainable and novel solutions to waste containment, and fate and transport of contaminants in the geoenvironment. Her current research is an investigation of the long-term behavior of polymer modified bentonite for containment barrier applications. Dr. Bohnhoff has taught a variety of undergraduate courses including Geotechnical Engineering, Environmental Engineering, Foundation Design, and Groundwater Hydrology.

Kristin Sample-Lord, Villanova University (USA)

Dr. Kristin Sample-Lord is an associate professor in the Department of Civil and Environmental Engineering at Villanova University (VU). She earned her PhD and MS in Civil Engineering with an emphasis in Geoenvironmental Engineering from Colorado State University. Dr. Sample-Lord teaches graduate and undergraduate courses in geotechnical engineering, geoenvironmental engineering and engineering geology. Her research programs focus on engineered barriers, waste re-use, and green stormwater infrastructure. Highlights of her work in engineering education include development of a shareable activity library for the United States Universities Council on Geotechnical Education and Research (USUCGER) and co-leading the 2020 Geotechnical Engineering Faculty Teaching Strategies and Resources Workshop (in collaboration with Dr. Bohnhoff).

Jonathan Hubler, Villanova University (USA)

Dr. Jonathan Hubler is an assistant professor in the Department of Civil and Environmental Engineering at Villanova University (VU). VU is a research institution in Villanova, Pennsylvania. Dr. Hubler earned his PhD in Civil Engineering with an emphasis in Geotechnical Engineering from the University of Michigan, and both his Master of Science in Civil Engineering and Bachelor of Science in Civil Engineering from Drexel University. Dr. Hubler's research interests include geotechnical earthquake engineering, natural hazards, coastal engineering, static and dynamic response of soils in the laboratory and field, soil liquefaction, and beneficial reuse of recycled materials in geotechnical engineering. Dr. Hubler has taught a variety of undergraduate and graduate courses including Soil Mechanics, Foundation Design, Senior Capstone, Geotechnical Earthquake Engineering, and Geosynthetics.

Nate Strandberg, University of Wisconsin-Platteville (USA)

Nate Strandberg is an environmental engineering student in the Department of Civil and Environmental Engineering at the University of Wisconsin-Platteville. Nate is an undergraduate research assistant in the geoenvironmental engineering laboratory at UW-Platteville. In addition, he participated in a Research Experience for Undergraduates (REU) at Villanova University during the summer of 2024.

Jed Walleser, University of Wisconsin-Platteville (USA)

Jed Walleser is a civil engineering student with an emphasis in geotechnical engineering in the Department of Civil and Environmental Engineering at the University of Wisconsin-Platteville. Jed is an undergraduate research assistant in the geoenvironmental engineering laboratory at UW-Platteville. In addition, he participated in a Research Experience for Undergraduates (REU) at Villanova University during the summer of 2024.

Open Educational Resources for geotechnical engineering education

W. Fellin

University of Innsbruck, Austria
Wolfgang.fellin@uibk.ac.at

ABSTRACT: Only a few open educational resources (OER) for geotechnical engineering can be found online and most of these materials are restricted to non-commercial use, which is not a recommended license for OER. This article shows which licenses should be used in order to maximize potential for reuse and sharing as prescribed by the definition of OER. Depending on the type of material produced, the production of new material can involve an enormous amount of work. The article shows the author's production method for videos, interactive videos and interactive work sheets, which may be valuable for persons who want to start producing similar OER material. Mainly open source tools are presented for this task. The 8 videos, the 8 interactive videos and the 2 interactive worksheets are hosted as OER material at the OER repository of the University of Innsbruck and are therefore available for everyone. This will hopefully foster the production of new OER material, either by reusing/remixing/redistributing existing materials or by producing genuinely new material for our community.

Keywords: didactic videos, interactive videos, interactive work sheets, Creative Commons license

1 Introduction

Good teaching can benefit greatly from high-quality materials, such as didactic videos. Since the production of such videos is a lot of work, it would be great if one could find material that can be used freely. So, if one produces such material, it would be perfect that this material is then provided as an open educational resource (OER). This article starts with the definition of OER and recommendations for the licences that should be use for such material. Then, the author's production method for videos, interactive videos and interactive work sheets, mainly with Open Source tools, is presented and the reference to the published versions is given. Finally, the implementation of the OER material in courses is outlined.

2 Open Educational Resources

2.1 Definition and purpose

"Open Educational Resources (OER) are learning, teaching and research materials in any format and medium that reside in the public domain or are under copyright that have been released under an open license, that permit no-cost access, re-use, re-purpose, adaptation and redistribution by others" (UNESCO, 2019). OER directly contribute to the implementation of the Sustainable Development Goal 4 (quality education) of the United Nations. "Open license refers to a license that respects the intellectual property rights of the copyright owner and provides permissions granting the public the rights to access, re-use, re-purpose, adapt and redistribute educational materials" (UNESCO, 2019). In other words, OER should be licensed in such a way that anyone may engage in the following five activities (known as 5R, Wiley, 2014):

1. Retain – make, own, and control a copy of the resource (e.g. download and keep your own copy)
2. Revise – edit, adapt, and modify your copy of the resource (e.g. translate into another language)
3. Remix – combine your original or revised copy of the resource with other existing material to create something new (e.g. make a mashup)
4. Reuse – use your original, revised, or remixed copy of the resource publicly (e.g. on a website, in a presentation, in a class)
5. Redistribute – share copies of your original, revised, or remixed copy of the resource with others (e.g. post a copy online or give one to a friend)

Two Creative Commons licenses ensure all five activities are therefore suitable for OER materials, as will be explained in Section 3.

2.2 Situation in geotechnical education

The search for OER materials for geotechnical engineering in OER search engines is not very satisfactory, e.g. the search for “geotechnical engineering” on OER Commons¹ returns 18 results, 7 of which are restricted to non-commercial use and the rest allow use for educational purposes only. The search for “soil mechanics” returns 3 results, all of which are restricted to non-commercial use. The restriction to non-commercial use can significantly hinder use by others.

There are many videos on YouTube related to geotechnical engineering, however, most of the videos have a standard YouTube license (e.g. uSeeGeo²), which makes it difficult to use them as OER. Only some YouTube videos have a Creative Common license (e.g. John Burland's Bare Essentials of Soil³).

An online survey among members of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) revealed that a high percentage (45%) of the geotechnical engineering instructors replied negatively to the question “Were you satisfied with any material found after searching” (Pantazidou & Calvello, 2024). In addition, to the question “If you were not satisfied with some of the material found, in what way was the material inappropriate?”, 28% of the respondents included in their answer “the material did not come with a reuse permit”.

The license of restricted materials should be changed to a truly open license in line with UNESCO recommendations and more material should be produced with a clear and open license. Depending on the type of material produced, the production of new material can involve an enormous amount of work. If more material would be available with a true open license, mixing such material to suit a particular teacher's desired purpose would drastically reduce this workload.

A good example for licenses is the collection of peer-reviewed educational materials of the International Society for Soil Mechanics and Geotechnical Engineering (<https://www.issmge.org/education/peer-reviewed-educational-materials>), where, for example, 18 slides related to Environmental geotechnics with an open license are hosted.

3 Creative Commons licenses

Any creative material created by a person, e.g. a painting, a graphic, a book, a song and its lyrics or a photograph, is protected by copyright. A Creative Commons (CC) license is one of several public copyright licenses that enable the free distribution of such materials. Creative Commons licenses define the terms and conditions for the use of the licensed material by the following attributes (Creative Commons, online):

BY: credit must be given to the creator.

SA: adaptations must be shared under the same terms.

NC: only non-commercial uses of the work are permitted.

¹ <https://oercommons.org/>

² www.youtube.com/@uSeeGeo

³ www.youtube.com/@ExpeditionworkshedOrg1

ND: no derivatives or adaptations of the work are permitted.

These attributes can be combined to six licenses, listed from most to least permissive here:

CC BY, CC BY-SA, CC BY-NC, CC BY-NC-SA, CC BY-ND, CC BY-NC-ND.

CC BY allows to distribute, remix, adapt, and build upon the material in any medium or format also for commercial use. Therefore, it is a fully open licence and suitable for OER. The SA attribute adds that if one remixes, adapts or builds upon the material, the modified material must be licensed under identical conditions, i.e. SA again. The SA attribute can also be used for OER. Creators from universities tend to use the NC (non-commercial) attribute. The definitions of the license CC BY-NC 4.0⁴ states “NonCommercial means not primarily intended for or directed towards commercial advantage or monetary compensation.” With this imprecise definition, it is not always easy to determine whether something is considered commercial use (cf. Hendricks, 2018). The teaching opinion in the Austrian OER certificate course is that such materials cannot be used at a university that charges tuition fees, which is also the opinion of the Central Repository for OER of higher education in Baden-Württemberg/Germany (ZOERR, online). Wiley (2016) states in his blog that the only way to determine definitively whether a use is commercial or not is to go to court and have a judge decide. These uncertainties with the NC attribute restrict the desired freedom of reusing the OER. Therefore, the NC attribute is not recommended for OER. The ND (no derivatives) attribute does not allow revising or remixing content, two of the most significant freedoms of OER. Material licensed with an ND attribute cannot be considered as OER.

To conclude, only CC BY and CC BY-SA are fully suitable for OER (cf. ZOERR, online) and are therefore the two standard options of the OER repository of the University of Innsbruck. However, due to the restrictions on remixing with the SA attribute, it is reasonable to assume that CC BY material will be used more often by others for reuse or remixing, thereby increasing the visibility of the author. Therefore, and simply because of the greater flexibility of CC BY, this license is highly recommended for OER, just as the Alliance of Science Organisations in Germany recommends CC BY for Open Access publishing (cf. DEAL, 2024). If an author intends to exclude commercial use, she or he might consider using CC BY-SA instead of CC BY-ND. Material with a SA attribute can only be commercially used as it is, not altered at all, which makes it harder to make money (cf. Hendricks, 2018).

Another open license for OER is CC0 (public domain), however, this license is not recommended as the creators give up their copyright and this license may violate national laws.

4 Videos

Videos are relatively easy to create these days. There is a variety of ways to produce them, and the following combination of tools has proven effective for the author. It is important to note that the author is not a professional video creator, and the path presented is the result of a (somewhat tedious) self-learning process and therefore may be far from perfect. You should always use the tool you are familiar with to reduce production time. A rough estimate is 1 to 3 hours per minute of the videos published as OER by the author.

The raw material for the videos was created by video recording with a mobile phone or a tablet, and by screen capturing from a computer or tablet. The main task is to edit such videos and convert them into a didactically usable form. The author used the screen capturing app Mobizen⁵ on the tablet to produce animated figures, OBS studio⁶ for screen capturing of slides on a computer, audacity⁷ for sound recording, and kdenlive⁸ for cutting, see Figure . Although kdenlive provides sound recording, the experience was unsatisfactory, since the recorded tracks had unexpected sound errors. OBS studio, kdenlive and audacity are free and open source software available for Windows, Linux and Mac.

⁴ <https://creativecommons.org/licenses/by-nc/4.0/legalcode>

⁵ <https://www.mobizen.com/en/product/mobizen-recorder/>

⁶ <https://obsproject.com/>

⁷ <https://www.audacityteam.org/>

⁸ <https://kdenlive.org/>

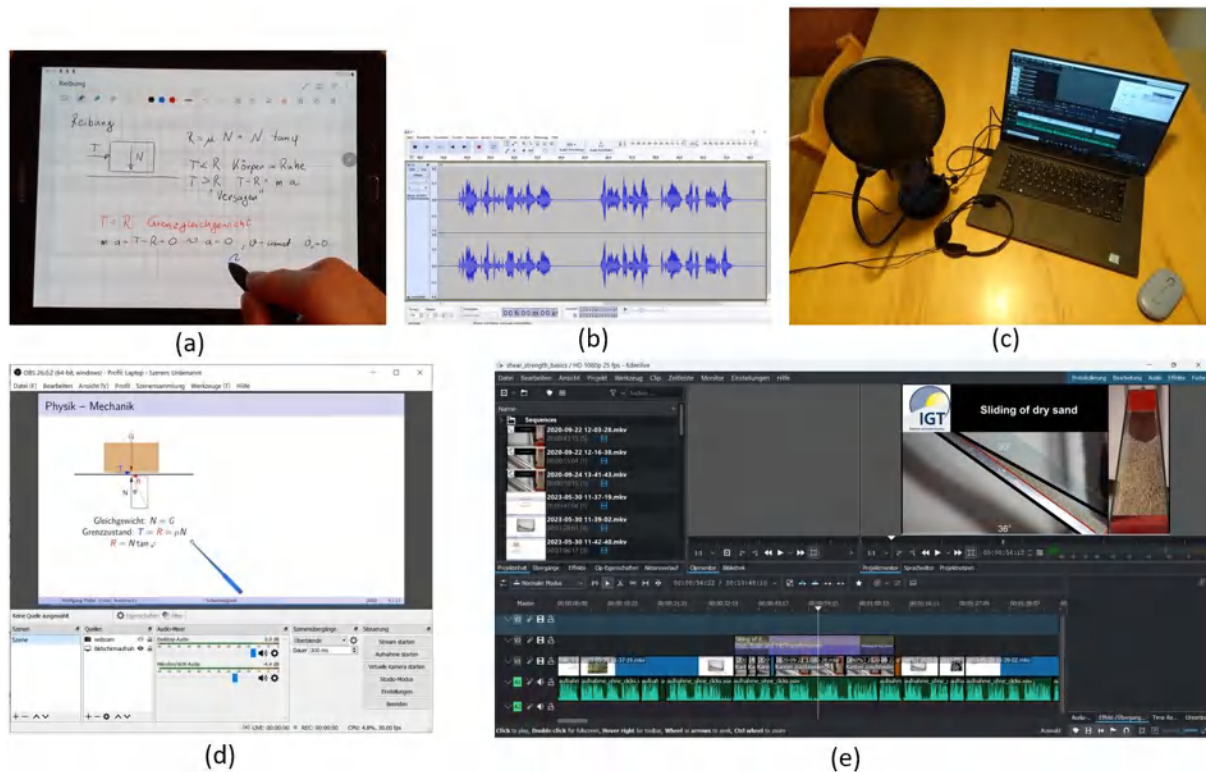


Figure 1. Video creation: (a) animated figures with tablet and video recording app; (b) audacity; (c) microphone, headset and laptop; (d) OBS studio; (e) kdenlive

One way was including the animated figures in Powerpoint slides and capture these slides together with the voice using OBS. These screen captures were then edited with kdenlive, the text was recorded again with audacity and finally these sound tracks were synchronized with the video tracks in kdenlive. The other way was to load screen shots of the Powerpoint slides into kdenlive and arrange the animated figures on an overlay video track. It depends on the content and way of presenting which way turns out to work better, e.g. capturing slides with OBS allows for recording pointer (mouse) actions to easily highlight the part of the slide that is currently being discussed.

Advice for the optimal video length spans from, e.g. 6 minutes (Guo et al., 2014), 10 to 19 minutes (TechSmith, 2024) up to 20 minutes (Thompson et al., 2021) with a tendency to state *the shorter the better*. However, defining an optimal video length goes hand in hand with trivializing the learning process and “the search for the optimal instructional video length that fits for all should end since it is like looking for hay in a haystack; it is everywhere and all comments on the video length are related to context” (Demir & Birgili, 2024).

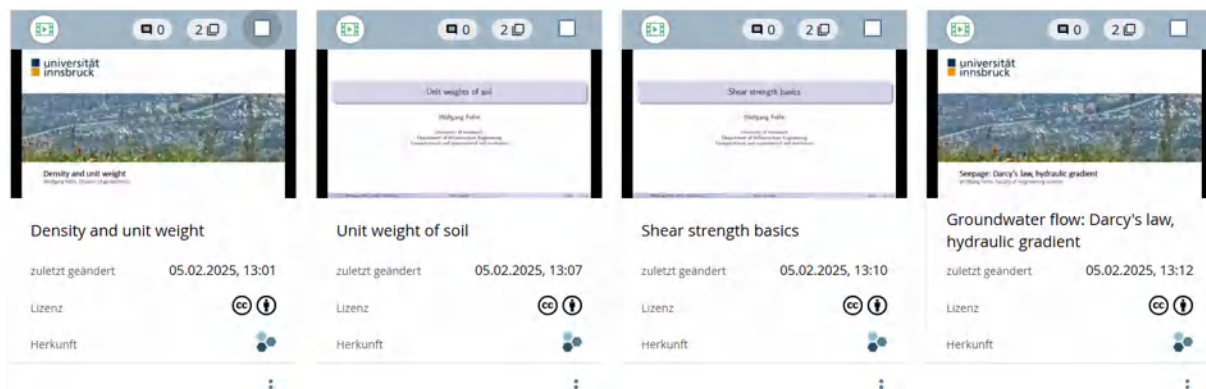


Figure 2. Resources for four of the eight topics currently available in the collection (see Table)

The transcript of the videos should be provided along with the video. The videos with transcripts including screen shots of the respective part of the video are online at the OER repository of the University of Innsbruck (Fellin, 2024), see Figure and Table . All videos are also available in German along with a few more (interactive) videos in German at the OER repository.

Table 1. Videos with transcriptions at the OER repository of the University of Innsbruck, which can be viewed online or downloaded

Video	Description
Density and unit weight	The unit of weight is mainly used in engineering and is explained here in comparison to the more common term density.
Unit weight of soil	Volume fractions in the soil and resulting unit weights, as well as unit weight under buoyancy are explained in this video.
Shear strength basics	The video contains explanation of the terms critical friction angle, peak friction angle based on the direct shear test and in connection with the stability of very long slopes.
Groundwater flow: Darcy's law, hydraulic gradient	Darcy's law is explained with a simple example and the concept of hydraulic gradient is visualized.
Shear strength: critical and peak, Coulomb	This video explains the shear strengths achieved by loose and dense soils. The two terms "critical shear strength" and "peak shear strength" are explained. Finally, the shear strength of the dense soil is determined by a linearization according to Coulomb.
Failure in soil	Failure in soils always results in the formation of shear bands. This video shows how a shear band develops in a biaxial test and which simplifications for soil mechanics tests and calculations follow from this.
Critical void ratio	The critical void ratio is determined from the evolution of the void ratio in a shear test.
Stiffness and strength	Stiffness and strength are essential properties of soils. Their definitions, similarities and differences are briefly explained here.
Videos and transcripts	https://oer-repo.uibk.ac.at/edu-sharing/components/collections?id=6b874dbb-b8c1-4c7c-98a7-e73c40676c21
Interactive versions	https://oer-repo.uibk.ac.at/edu-sharing/components/collections?id=49292c54-5335-4fc0-b671-ae33685f8e6d

The video “Shear strength basics”, for example, shows a chute experiment in which viewers have to guess at what angle the sand starts to slide, see Figure . The video then explains that there are two friction angles for a dense soil: a peak friction angle and a critical friction angle. This is explained with dilatation and both angles can be seen in the experiment, as the angle at which the sand starts to slide corresponds to the peak friction angle and the angle of repose is approximately the critical friction angle.



Figure 3. Screen shots of video “Shear strength basics”

5 Interactive Videos

The didactic value of videos can be increased enormously by making them interactive (e.g. Dahlan et al., 2023). The effort to create an interactive video based on an existing video is much smaller than the effort to produce the video. Interactive video can be created by using the H5P format⁹ with the Lumi editor¹⁰. The video can be enriched with, e.g. multiple-choice questions, drag and drop tasks, and much more (Figure 4). This forces viewers to become active and not just passively consume the video. The interactions can be used perfectly to emphasize the central learning content of the video.

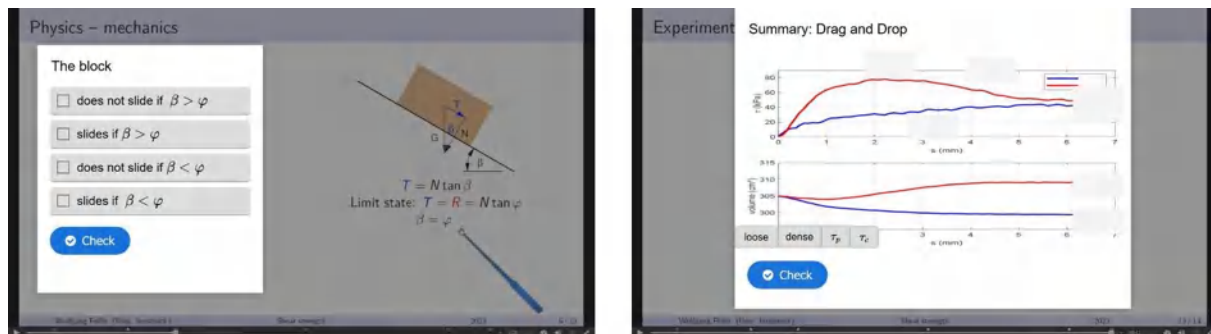


Figure 4. Interactive version of the shear strength basics video: multiple choice question and drag and drop task

The interactive versions of the videos are published at the OER repository of the University of Innsbruck (Fellin, 2024) in the collection *Soil mechanics – interactive*, see Table .

6 Interactive worksheets

Interactive worksheets can be used to encourage active learning of content by mixing short theoretical inputs with small tests, such as multiple-choice questions and calculation examples, see Figure . The students can check their answers and view the correct solution, see Figure .

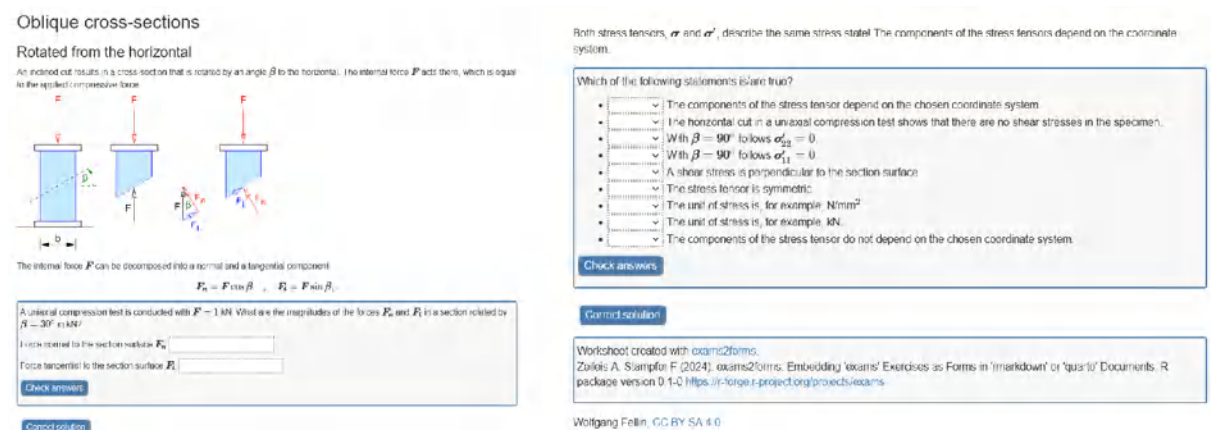


Figure 5. Interactive worksheet - calculation examples for stresses in a uniaxial compression test

⁹ <https://h5p.org/>

¹⁰ <https://lumi.education/>

A uniaxial compression test is conducted with $F = 1$ kN. What are the magnitudes of the forces F_n and F_t in a section rotated by $\beta = 30^\circ$ in kN?

Force normal to the section surface F_n ✓

Force tangential to the section surface F_t ✗

[Do not check answers](#) 1 of 2 correct

Correct solution

$$F_n = F \cos \beta = 1 \cdot \cos 30^\circ = 0.866025 = 0.87 \text{ kN}$$

$$F_t = F \sin \beta = 1 \cdot \sin 30^\circ = 0.5 = 0.50 \text{ kN}$$

Figure 6. Interactive worksheet with answer check and shown correct solutions

To make such worksheets generally available, they must be useable outside special learning management systems such as OLAT or Moodle. A possibility for that is producing HTML-worksheets, that can be used within an OER repository or stand alone in any browser. The interactive worksheets were created with R/exams¹¹ (Zeileis et al., 2014). This opensource software has been developed to create large numbers of personalized exams/quizzes/tests for various learning platforms based on dynamic exercise templates. R/exams can be freely used and an adaptation to technical lectures is possible (Fellin & Zeileis 2020). Zeileis & Stampfer (2024) developed a package to create HTML versions of such tests, which can be used to produce interactive worksheets. The two (starting) interactive worksheets are published at the OER repository of the University of Innsbruck (Fellin, 2024) in the collection *Soil mechanics – interactive*, see Table .

7 OER repository

The videos, the interactive videos and the interactive worksheets are hosted as OER material at the OER repository¹² of the University of Innsbruck and are therefore available for everyone. The repository has the advantage that the material is stored safely and permanently, i.e. each material is labeled by a unique persistent ID HANDLE and – if wished – a DOI number can be given. All necessary information, such as Title, authors, license and more, is stored in a meta file, which is displayed along with the material. In this way, the terms for reusing and remixing are clear. Moreover, keywords can be given to enhance visibility for specialized OER search engines (e.g. OER Commons¹³) or other search engines¹⁴.

8 Implementation in courses

The German versions of the present material are used together with videos from other authors in courses which are based on a flipped classroom approach (Baker, 2000; Lage et al., 2000; Fellin, 2023). The flipped classroom approach has a statistically significant advantage compared to traditional settings (meta-analysis of 295 publications by Låg & Sæle, 2019; meta-analysis of 55 publications by Cheng et al., 2019; meta-analysis of 63 experimental articles by Shao & Liu, 2021). The improvements include, for example: better exam performance (Deslauriers et al, 2011; Kugler et al, 2019; Tang et al, 2017; Låg & Sæle, 2019; Cheng et al, 2019; Shao & Liu, 2021; van Alten et al, 2019; Hassan & Othman, 2021), positive effects on students' learning efficiency, which also affect performance in other courses (Ji et al, 2022), as well as increased motivation, improved understanding, communication skills and reasoning (Tang et al, 2017; Hassan & Othman, 2021). However, students criticize a higher workload (e.g. Tang et al, 2017), see Figure .

¹¹ <https://www.r-exams.org/>

¹² <https://oer-repo.uibk.ac.at/>

¹³ <https://oercommons.org/>

¹⁴ see list in <https://guides.ou.edu/oer/search> for example

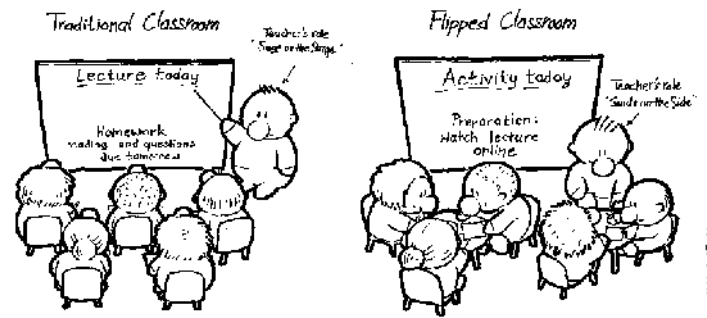


Figure 7. Flipped classroom (WeyHanTan, CC BY 4.0, WIKI Commons)

In a flipped classroom setting, students have to prepare themselves before the classroom, e.g. by reading chapters in a textbook, work out (simple) calculation examples, watching videos, performing online quizzes (e.g. Medicus 2014; Fellin and Medicus 2015). In the classroom, students may discuss their computed results in small groups and, in addition, work through new tasks. The main advantages are that the lecturer is available to help if needed and the students are active during the classroom. The OER material is used by the students in the flipped classroom setting for preparation to the classroom events and to the exams.

The 108 students in the 2023/24 course *Soil Mechanics and Foundation Engineering* (bachelor, 3rd semester, 1.5 ECTS) for students from the engineering faculty accessed interactive videos and videos 534 times. The 13 students in the 2024/25 course *Ice, Snow and Avalanche Mechanics* (master, 1st semester, 2.5 ECTS) for students from the engineering faculty accessed the two provided interactive work sheets 70 times. The 6 students in the 2024/25 course *Introduction to Soil Mechanics* for students (master, 1st semester, 1.5 ECTS) from the geology faculty accessed interactive videos and videos 111 times. It is clear that the access rate does not reflect that the videos are viewed in full. However, although the use of the material is only optional, the high number of accesses shows that at least the students are interested in the material. The videos were mainly watched in the beginning of the *Soil Mechanics and Foundation Engineering* course and before and during the examination period, Figure (a), and more equally distributed in the *Introduction to soil mechanics* course, Figure (b).

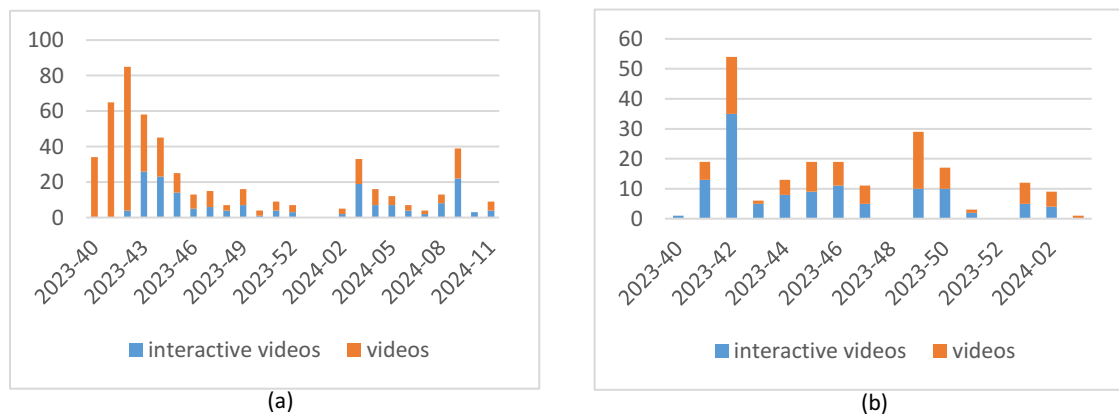


Figure 8. Time of video views: (a) *Soil Mechanics and Foundation Engineering* (b) *Introduction to Soil Mechanics*

9 Concluding remarks

The production of didactic material is a lot of work, especially for videos (roughly estimated as 1 to 3 hours per minute videos). However, students use this material and there is value in spending the time needed to create high-quality instructional resources. Such material should be shared with our community. Making the material available as Open Educational Resource (OER) along with an open licence is the best way to do this. The open licence ensures that the creators of such material are

properly cited, as we are used to when citing scientific articles. The OER material can then be easily found and used freely without worrying about copyright issues. The material created by the author has been published as OER and this will hopefully encourage the production of new OER material, either by reusing / remixing / redistributing existing material or by producing genuinely new material for our community.

Acknowledgements

The author thanks Achim Zeileis for his kind support in using R/exams, Felix Berkmann and Andreas Brigo from the AV-Studio of the Universität Innsbruck for valuable hints and technical assistance with audio recording at the university facilities, Maximilian Landegger for audio editing and Dario Ortlinghaus for translating and transcription of text.

References

- Baker, J. W. (2000). The Classroom Flip: Using Web Course Management Tools to Become the Guide by the Side. 11th International Conference on College Teaching and Learning, pp. 9-17, Florida Community College, Jacksonville.
- Cheng, L., Ritzhaupt, A., Antonenko, P. (2019). Effects of the flipped classroom instructional strategy on students' learning outcomes: a meta-analysis. *Educational Technology Research and Development*, 67, pp. 793–824. <https://doi.org/10.1007/s11423-018-9633-7>
- Creative Commons (online). About CC Licenses, <https://creativecommons.org/share-your-work/cclicenses/>, Accessed: 2025/01/13
- DEAL (2024). Unlocking the Full Potential of Your Research, choose CC BY! <https://deal-konsortium.de/en/why-coby>, Accessed 2025/04/16
- Deslauriers, L., Schelew, E., & Wieman, C. (2011). Improved Learning in a Large-Enrollment Physics Class. *Science*, 332(6031), pp. 862–864. <https://doi.org/10.1126/science.1201783>
- Dahlan M. M., Halim N. S. A., Kamarudin N. S., and Ahmad F. S. Z (2023). Exploring interactive video learning: Techniques, applications, and pedagogical insights. *International Journal of Advanced and Applied Sciences*, 10(12), pp. 220–230, <https://doi.org/10.21833/ijaas.2023.12.024>
- Demir, Ö., Birgili, B. (2024). Optimal Video Length Effect on Flow Experience and Perceived Learning: A Repeated Measure Experimental Design with Randomization. *Participatory Educational Research*, 11(1), pp. 142–157. <https://doi.org/10.17275/per.24.9.11.1>
- Fellin, W., Medicus, G. 2015. Multiple Choice Tests: More than a Time Saver for Teachers, *International Journal of Engineering Pedagogy*, 5(3), pp. 15–24. <http://dx.doi.org/10.3991/ijep.v5i3.4376>
- Fellin, W. (2023). 20 years of experience with Flipped Classroom - effects and undesirable side effects (20 Jahre Erfahrung mit Flipped Classroom – Wirkung und unerwünschte Nebenwirkungen). In: Vöing, Nerea; Schmidt, Rebekka; Neiske, Iris: *Aktive Teilhabe fördern: ICM und Student Engagement in der Hochschullehre*. 11. Jahrestagung #icmbeyond an der Universität Paderborn, pp. 161–188, Visual Ink Publishing, Dornstadt. <https://diglib.uibk.ac.at/urn:urn:nbn:at:at:ubi:3-36302>
- Fellin, W. (2024): Soil Mechanics Collection at the OER repository of the University of Innsbruck, <https://oer-repo.uibk.ac.at/edu-sharing/components/collections?id=6b874dbb-b8c1-4c7c-98a7-e73c40676c21>, Accessed: 2025/01/17
- Fellin, W., Zeileis, A. (2020). Transitioning a Soil Mechanics Course to R/exams. In *R/exams Blog*. http://www.r-exams.org/general/uibk_soilmechanics/, Accessed 2025/01/17
- Guo, P. J., Kim, J., Rubin, R. (2014). How video production affects student engagement: An empirical study of MOOC videos. *Proceedings of the First ACM Conference on Learning at Scale*, pp. 41–50, Atlanta, Georgia, USA. <https://doi.org/10.1145/2556325.2566239>

- Hassan, M. H. A., Othman, N. A. (2021). Flipped Classroom Approach in Rigid Body Dynamics: A Case Study of Five-Semester Observation, *International Journal of Engineering Pedagogy*, 11(1), pp. 87–94. <https://doi.org/10.3991/ijep.v11i1.15005>
- Hendricks, C. (2018). Explaining CC BY-NC and BY-SA, Blog: You're the Teacher – Teaching & Learning, and SoTL, in Philosophy, <https://blogs.ubc.ca/chendricks/2018/08/16/explaining-nc-and-sa/>, Accessed: 2025/01/13
- Ji, M., Luo, Z., Feng, D., Xiang, Y., Xu, J. (2022). Short- and Long-Term Influences of Flipped Classroom Teaching in Physiology Course on Medical Students' Learning Effectiveness. *Frontiers in Public Health*, 10. <https://doi.org/10.3389/fpubh.2022.835810>
- Kugler, A. J., Gogineni, H. P., Garavalia, L. S. (2019). Learning Outcomes and Student Preferences with Flipped vs Lecture/Case Teaching Model in a Block Curriculum. *American journal of pharmaceutical education*, 83, pp. 7044–7044. <https://doi.org/10.5688/ajpe7044>
- Lage, M. J., Platt, G. J., Treglia, M. (2000). Inverting the Classroom: A Gateway to Creating an Inclusive Learning Environment. *The Journal of Economic Education*, 31(1), pp. 30–43. <https://doi.org/10.2307/1183338>
- Låg, T., Sæle, R. (2019). Does the Flipped Classroom Improve Student Learning and Satisfaction? A Systematic Review and Meta-Analysis. *AERA Open*, 5(3), pp. 1–17. <https://doi.org/10.1177/2332858419870489>
- Medicus, G. (2014). Fördert ein Multiple-Choice-Selbsttest das Verständnis für geotechnische Problemstellungen? In *Schaufenster Lehre der Universität Innsbruck*, 27. https://www.uibk.ac.at/media/filer_public/11/2b/112b2018-f255-4793-a957-659ab13c7513/2014-10-07_medicus_gertraud.pdf, Accessed 2025/10/17
- Pantazidou, M., Calvello, M. (2024). What kinds of educational material are useful for and desired by university instructors? The case of Geotechnical Engineering, *Soils and Rocks*, Vol. 47, No 2, e2024003623. <https://doi.org/10.28927/SR.2024.003623>
- Shao, M., Liu, X. (2021). Impact of the Flipped Classroom on Students' Learning Performance via Meta-Analysis. *Journal of Social Sciences*, 9, pp. 82–109. <https://doi.org/10.4236/jss.2021.99007>
- Tang, F., Chen, C., Zhu, Y., Zuo, C., Zhong, Y., Wang, N., Zhou, L., Zou, Y., Liang, D. (2017). Comparison between flipped classroom and lecture-based classroom in ophthalmology clerkship. *Medical Education Online*, 22(1), pp. 1395679–1395679. <https://doi.org/10.1080/10872981.2017.1395679>
- TechSmith (2024). Video Viewer Trends Report. <https://www.techsmith.com/2024-video-viewer-trends-report.html>, Accessed: 2025/01/16
- Thompson, P., Xiu, Y., Tsotsoros, J. D., Robertson, M. A. (2021). The effect of designing and segmenting instructional video. *Journal of Information Technology Education*, 20, pp. 173–200. <https://doi.org/10.28945/4756>
- UNESCO (2019). Recommendation on Open Educational Resources (OER), <https://www.unesco.org/en/legal-affairs/recommendation-open-educational-resources-oer?hub=785>, Accessed: 2025/01/13
- van Alten, D. C. D., Phielix, C., Janssen, J., & Kester, L. (2019). Effects of flipping the classroom on learning outcomes and satisfaction: A meta-analysis. *Educational Research Review*, 28, 100281. <https://doi.org/https://doi.org/10.1016/j.edurev.2019.05.003>
- Wiley, D. (2014). Defining the 'Open' in Open Content and Open Educational Resources. Open Content blog, <http://opencontent.org/definition/>, Accessed 2025/01/13
- Wiley, D. (2016). Advocating for CC BY. Open Content blog, <https://opencontent.org/blog/archives/4818>, Accessed 2025/04/15
- Zeileis, A., Umlauf, N., Leisch, F. (2014). Flexible Generation of E-Learning Exams in R: Moodle Quizzes, OLAT Assessments, and Beyond, *Journal of Statistical Software*, 58(1), pp. 1–36. <http://hdl.handle.net/10419/73861>
- Zeileis A, Stampfer F (2024). exams2forms: Embedding 'exams' Exercises as Forms in 'rmarkdown' or 'quarto' Documents. R package version 0.1-0, <https://cran.r-project.org/web/packages/exams2forms/exams2forms.pdf>
- ZOERR (online). Questions about licensing – 2. Which CC licenses are open licenses? https://www.oerbw.de/faqliz_en.html#fL2, Accessed 2025/04/16

Author's bio

Wolfgang Fellin, University of Innsbruck (Austria)

Dr. Wolfgang Fellin is an associate professor at the University of Innsbruck who specializes in the field of Geotechnical Engineering. He holds his Civil Engineering degrees from University of Innsbruck. His interdisciplinary research interests include material modelling of soils and natural hazards like snow avalanches and large mass movements. Dr. Fellin was the first to use flipped teaching at his faculty more than 20 years ago and investigated the effect of various teaching measurements in a scientific way. In 2013, he was awarded with the prize for excellence in teaching at public universities in Austria. He achieved the OER Practitioner certificate in 2024.



Settlement calculations of a motorway embankment and comparison with field measurements: An education case study

V. Xenaki¹ & M. Pantazidou²

¹*Edafomichaniki S.A., Athens, Greece*
vxenaki@edafomichaniki.gr

²*National Technical University of Athens, Zografou, Greece*
mpanta@central.ntua.gr

ABSTRACT: This paper focuses on the presentation of a case study that is suitable for instruction in the geotechnical engineering field, mainly because settlement calculations for a motorway embankment are accompanied by field measurements during a two-year period that includes both the construction period and the operation of the motorway. The examined case study refers to a reinforced embankment of 12.3 m height founded on highly compressible alluvial deposits. Settlement calculations are performed using conventional methods, using the theory of one-dimensional consolidation. The settlement-time curves resulting from the relevant geotechnical calculations performed for each one of the intermediate construction stages are compared with the corresponding field measurements. In all the examined cross sections, the calculated settlements are higher than the measured settlements; overprediction ranges from 36% to 207%. The case study provides an opportunity to compare methods taught and used in practice and to discuss variability expected in practice.

Keywords: Monitoring, Settlement, Consolidation

1 Introduction

The selection of the case study presented herein is consistent with research-based principles for learning from the education literature. Specifically, the principle that concerns students' motivation, which according to Ambrose et al. (2010) "determines, directs, and sustains what they do to learn". Ambrose et al. (2010) explain that motivation is related to students' personal investment and the subjective value of the learning goal and the task at hand. In order to influence the subjective value of the learning goal, they recommend that instructors make educational material more interesting to students by selecting authentic, real-world tasks to which ideally they can relate. To this end, the case study selected and presented herein concerns a significant settlement of a motorway embankment, which students can approximate with knowledge from an introductory soil mechanics course. What is more, its location is close to a well-known locale from Ancient Greek History, Thermopylae, also known in English as "Hot Gates".

The notable features of the selected project are summarized as follows. 1) Fixed elevations and space constraints resulting from the existing motorways to be connected, which necessitate some steep-slope (3:2) (height:base) embankments that will have to be reinforced with geosynthetics. 2) The soils are recent quaternary alluvial deposits of considerable thickness, predominantly fine-grained over at least the top 30-35 meters, which are expected to necessitate construction of the embankments in stages. 3) The significant heterogeneity of soils is a source of uncertainty for the soil profiles at cross sections further away from the boreholes. Due to (2) and (3), monitoring is a key element for the construction of the embankments. The combined historical-geological interest of the project location, which is tightly linked to the significant magnitude of consolidation settlements, and the 2-year long monitoring record make this project a good candidate for an education case study.

In previously published educational case studies, we chose an 8.75 m high road embankment with a calculated settlement of 0.99 m (Orr & Pantazidou, 2013) and an 8 m high railway embankment with a calculated settlement 0.64 m (Xenaki et al., 2016). The 8.75 m embankment necessitated construction in stages, whereas the 8 m embankment was to be constructed in a single stage. In the present paper, we focus on a 12.3 m high motorway interchange embankment with a calculated settlement of 1.34 m, which again necessitated staged construction. Motivating questions for the use of this case study in instruction include “why is the settlement so large?” and “do we feel comfortable or nervous with this large calculated settlement for the specific locale?”. The main goal of this paper is to highlight the relevance of theory taught in courses to practice and relate depositional history to soil parameters. A second goal is to attempt to draw lessons from comparisons of calculated and observed settlements at several cross sections of the interchange.

2 Geology and design soil layers

2.1 Project area

Geological observations and the pertinent data from the geotechnical investigations (execution of sampling boreholes) indicate that the interchange passes through recent quaternary deposits which have a significant thickness. Results from a total of 52 boreholes were evaluated, 18 of which were drilled for an earlier alignment of the motorway and are not as close to the final location of the embankment. The maximum borehole depth is 45.35 m, while most boreholes reach a depth of 30-35m.

More specifically, alluvial deposits (al) are encountered in the project area, characterized by significant heterogeneity in both horizontal and vertical directions. The alluvial deposits in the study area consist either of clay and clayey silts, or of silty sands, or of sand and gravel.

Based on a) the pre-existing geological report, b) the macroscopic description, c) the grain size distribution curves, and d) the results of laboratory tests on characteristic soil samples from the relevant boreholes, the geological formation of the alluvial deposits at the project area is divided into five distinct geotechnical formations (I to V) (see Figure 1). Specifically, in the upper 20 m to 25 m, very soft to soft clayey-silty formations I and II (CL, CH, ML, CL-ML) are encountered, characterized by low values of the Standard Penetration Test (SPT) blow counts ($N_{SPT} < 12$) and therefore by poor mechanical properties, with interlayers of sand and locally gravel (formation III). At greater depths, clayey-silty formations (CL, ML, CL-ML) (formations IV and V) are found with higher SPT blow count values ($N_{SPT} > 12$) and better mechanical properties, which improve even further for depths greater than 35.0 m. At the project area the groundwater level is near the surface, therefore the soil is saturated.

2.2 Broader geological background

Zooming out from the project area, we see that the interchange is located in the Sperchios delta plain, about 10 km away from the current shoreline of the Malian Gulf. The Sperchios basin is well known in history from the battle that took place in 480 BC between ancient Greeks and Persians at Thermopylae (also known in English as “Hot Gates” from the hot springs located by the mountain’s foothills). At the time of the battle, the Thermopylae Pass is described by Herodotus as a narrow strip of land between Mount Kallidromon and the Malian Gulf Sea. The identified area of the battle is now more than 5 km away from the sea (Vouvalides et al., 2010). The alluvial sediments carried by Sperchios River have been filling the basin through the centuries – and in an asymmetric fashion, i.e. a significant part of the Sperchios delta plain was established earlier compared to the part near Thermopylae (Pechlivanidou et al., 2014) – and now the site of the battle location is the boundary of the mountain foothills and the alluvial plain. This high sediment discharge is due to the erodible sedimentary rocks (flysch) rich in clay minerals to the south of Sperchios River (Pantazidou et al., 2021; Marinos, 2025). In other words, history together with geology give us clues to expect young compressible sediments in the project area.

3 Design components and geotechnical parameters of soils

The examined interchange has an approximate total length of 1.5 km. The maximum height of the embankments is equal to 14.2 m. Based on the geometric characteristics of the embankments and on

the geotechnical conditions, the embankments are divided into three categories depending on the implemented construction methodology: a) embankments with slope inclination 2:3 (height:base), b) embankments with slope inclination 2:3 (height:base) with suitable basal reinforcement using geogrids and c) reinforced embankments with slope inclination 3:2 (height:base) using geogrids in combination with gabions at the slope faces.

The main geotechnical calculations performed for the design of the embankments include the following analyses at the most critical cross sections (Salgado, 2007; Barnes, 2005):

a) Slope stability analyses and more specifically:

- The initial slope stability analyses were focused on the soil bearing capacity, due to the presence of alluvial silty-clayey layers characterized by low shear strength parameters, which, in combination with the significant height of the embankments, makes it impossible to construct them in one stage. Therefore, staged construction of the embankments was proposed in the pertinent geotechnical study. The height of each intermediate construction stage was selected in such a way so that the soil bearing capacity, depending mainly on the undrained shear strength of the foundation layers, is adequate. For the first construction stage, slope stability analyses were performed using the initial undrained shear strength values of the soil layers, whereas for the subsequent construction stages increased undrained shear strength values were taken into consideration to account for the soil improvement due to preloading. The time-dependent improvement of undrained shear strength, Δc_u , of the foundation soil layers is affected by the imposed preloading (height of embankment) and the degree of consolidation which has been achieved during the preloading period. Prefabricated vertical drains are constructed to accelerate the consolidation.

The height of each construction stage has been selected by taking into consideration the most critical section (cross section 195, see later Table 3), where the silty-clayey layer characterized by high compressibility and low undrained shear strength values has the maximum thickness.

The maximum shear strength improvement is achieved under the central part of the embankment, whereas under the slopes of the embankment no shear strength improvement was accounted for in the stability analyses.

The above mentioned stability analyses for the intermediate construction stages refer to short-term conditions and were performed only under static loading conditions.

- At the final construction stage, at which the total height of the embankment constituting the permanent earthwork was completed, slope stability analyses were performed under both static and seismic loading conditions. It is noted that at the final stage, the internal slope stability is also critical due to the significant embankment height. For the reinforced embankments with steep slopes (3:2, height:base), apart from rotational analyses, translational analyses in predefined surfaces along the geogrid layers (two-part wedge mechanism) were also performed. The above analyses also validated the adequacy of the selected geogrids in terms of nominal tensile strength.

The traffic load in the slope stability calculations of the final construction stage is modelled by applying a distributed load on the crest of the embankment equal to $p=20$ kPa and $p=10$ kPa, for the case of static and seismic loading conditions, respectively.

The slope stability analyses were performed with the limit equilibrium method, using Larix-4S software (v. 2.21-Cubus) for the embankments with 2:3 (height:base) slope inclination and ReSSA software (V. 3.0, Adama Engineering, Inc. Newark, USA) for the embankments with 3:2 (height:base) slope inclination.

b) Calculation of the soil settlements due to the construction of the embankment.

Due to the nature of the encountered alluvial formations at the project area, where silty-clayey layers are predominant, in combination with the high groundwater level, the development of both immediate and consolidation settlements are expected to occur under the imposed embankment load. The calculated immediate settlements are expected to be completed during the construction of the embankment, whereas the consolidation settlements are time dependent.

c) Evaluation of liquefaction susceptibility of the bearing soil layers.

The relatively high groundwater level, in combination with the existence of loose sandy and silty soil layers at the area of the embankments, creates the conditions for possible initiation of liquefaction phenomena under seismic loading conditions. The relevant assessment methods indicate only the occasional existence of liquefiable layers of small thickness. Therefore this mode of failure is not taken into consideration for further analysis in the presentation of the current case study.

Groundwater level is located at 0.5 m to 1.0 m depth below the ground surface at the area of the embankment.

For the construction of the main part of the embankment, it is suggested that mainly coarse-grained crushed materials are used. The embankment material contains also fine material ($d < 0.063$ mm) up to 35%. The slope stability analyses and the settlement calculations of the embankment are carried out assuming the following geotechnical parameters for the material of the embankment: unit weight $\gamma = 20$ kN/m³, angle of internal friction $\phi = 32^\circ$, cohesion $c = 5$ kPa and elasticity modulus $E_s = 50$ MPa. The assumed shear strength values are validated by the Contractor by performing laboratory tests on compacted samples of the embankment material.

The determination of the detailed soil stratigraphy along the embankment as well as the determination of the geotechnical design parameters of the encountered soil formations have resulted from the geotechnical evaluation of the investigation data, based on the results of in situ tests (Standard Penetration, SPT) and laboratory tests. Table S1 in the [Online Supplement](#) includes the detailed list of the delineated sublayers with the respective design parameters. The heterogeneity of the encountered alluvial deposits is strongly depicted in the embankment longitudinal section given in the Supplement (Figure S13). The soil stratigraphy at the critical cross sections has been derived from the above mentioned longitudinal section.

In the context of this education case study, only settlement calculations are presented in detail and compared with monitoring results.

4 Calculated and measured embankment settlements

In the pertinent geotechnical study the following assumptions were made for settlement calculations:

- Regarding consolidation settlements, it is assumed that the deformations of the compressible layers will occur only in one dimension. Therefore, the theory of one-dimensional consolidation is used.

The laboratory oedometer test results for the silty-clayey layers undergoing consolidation indicate low values of preconsolidation stress, p'_c , compared to the effective overburden stress. However, low SPT values ($N_{SPT} < 4$) were frequently encountered near the surface. Thus it is considered that the surface clayey layer Ia is normally consolidated (overconsolidation ratio $OCR = 1.0$). To account for the improvement of geotechnical parameters with depth, slightly increased OCR values for the underlying layers (layers II, IVa and IVb) varying from 1.1 to 1.5 were assumed.

- Apart from the total magnitude of consolidation settlement (ultimate consolidation settlement at time $t = \infty$), the rate of consolidation settlements is also of great significance in the geotechnical design of the embankment. In order to determine whether the operation of the motorway will be affected by the magnitude of the remaining consolidation settlements, the Owner of the Project has set an available time period equal to 9-12 months for the completion of the embankment construction. In case the remaining settlements after the above time period are greater than 15.0 cm (maximum value specified by the Owner of the Project), the installation of vertical wick drains is required in order to increase the rate of consolidation settlements.
- Settlement calculations at the critical cross sections were carried out by taking into consideration a base improvement layer with thickness varying from 0.5 m to 1.0 m, depending on the thickness of unsuitable material that has to be removed for the foundation of the embankment.
- Apart from the embankment load, a traffic load equal to 20 kPa is also taken into consideration for the settlement calculations, as already mentioned in the description of stability analysis.
- The influence depth for the calculation of settlements is considered as the depth at which the imposed foundation load (reduced with depth) is equal to 20% of the effective overburden stress.

- The encountered alluvial deposits (al) are characterized by significant heterogeneity and the existence of sandy interlayers inside the silty-clayey layers is frequent. These sandy layers were neglected when calculating the consolidation settlements. Therefore, a conservatively high thickness of layers undergoing consolidation settlement is considered in the pertinent calculations, the priority being to avoid erring on the side of underprediction.
- Due to the above-mentioned heterogeneity, the soil stratigraphy may differ not only along the embankment, as depicted in the longitudinal section of the Supplement (Figure S13), but also across each examined embankment section.
- During the construction of the embankments, settlements were regularly measured (on a weekly basis) making it possible to validate the assumptions involved in the calculations. More specifically, settlement calculations were performed for each one of the intermediate construction stages and were evaluated by comparing them with the measured values.
- In the case of the examined cross sections, possible discrepancies between measured and calculated settlements do not affect significantly the dimensioning of the project, with the exception of the design for the required prefabricated wick drains. The selected grid of the drains is dependent on both the assumed degree of consolidation, related to the coefficient of consolidation, C_v , and the magnitude of consolidation settlement. However, faster consolidation also means faster increase of undrained shear strength allowing an earlier placement of the next layer and an earlier completion of the project.

Figure 1 shows the layers encountered at cross section 195 (at chainage 2+850) that will be discussed in detail for the purposes of this education case study, and the design parameters necessary for the calculation of settlements. Two more cross sections are included in the Supplement (Figures S2 and S3). The closest borehole to cross section 195 is ED-S1-BE06 (see Figure 13 in [OnlineSupplement](#)), drilled to a depth of 30 m. The depicted cross section reaches a depth of 52.5 m, which corresponds to the influence depth of the load (to a level of 20%, as already mentioned). Clearly, there is scanty information below a level of 30 m.

4.1 Simplified consolidation settlements

For the purposes of this education case study, the [OnlineSupplement](#) includes a case narrative where an undergraduate student performs simplified calculations of consolidation settlements using the data shown in Figure 1. Two sets of detailed calculations are included in the Supplement. For a load constant with depth, consolidation settlement is equal to 1.39 m. For a load attenuating with depth at a 2:1 (height:base) slope, consolidation settlement is equal to 1.08 m.

4.2 Settlement calculations from the project report

Settlement calculations due to the construction of the embankment were performed with the theory of one-dimensional consolidation, implemented in a Microsoft excel calculation sheet. In order to obtain more precise results regarding both immediate and consolidation settlements, each encountered layer is divided into sub-layers of smaller thickness. Settlements are calculated below the embankment axis and below the toe of the embankment. The stress distribution below the embankment is according to Osterberg (1957).

Apart from the magnitude of the settlement, the rate of consolidation is also estimated. As already mentioned, in order to satisfy the criteria regarding the allowable remaining settlement determined by the Owner of the Project (less than 15 cm) after the construction period (from 9 to 12 months), the installation of wick drains is required. Therefore the rate of consolidation is calculated by taking into consideration both vertical and radial drainage conditions. Although the time progression of the settlements is of great importance for staged construction, this paper focuses mainly on the total magnitude of consolidation settlement, to match the focus of the case narrative.

Table 1 includes the pertinent geometric parameters and the calculated settlements of the embankment axis for all the construction stages for cross section 195 in Figure 1. In the intermediate construction stages no surcharge is applied, whereas in the final stage a surcharge of 1.0 m is applied. Total consolidation settlement is equal to 1.18 m. For additional insight into the development of consolidation settlements (S_{cons}), the contribution of each layer is given separately ($S_{cons,i}$) and is also quantified as a percentage of the total consolidation settlement ($S_{cons,i} / S_{cons,tot}$ (%)). These results show that the

contribution of the surface layer in terms of consolidation settlement is predominant. It is also clear that immediate settlements are only a small part of the total settlements for all construction stages.

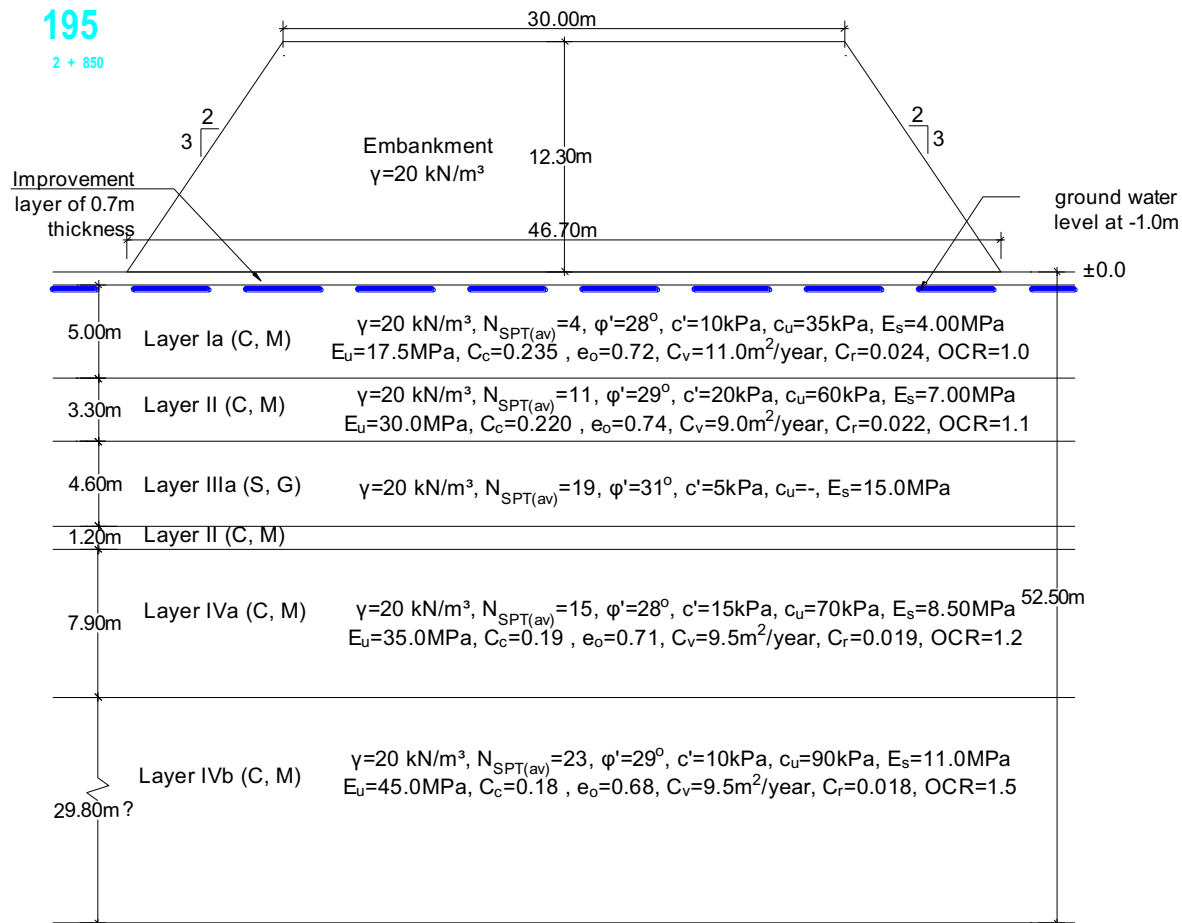


Figure 1. Characteristic cross section for settlement calculations

4.3 Monitoring results and comparison with settlement calculations

This section presents the measurements from three settlement gauges at cross section 195, ST10.2, ST11.2, and ST12.2, placed at the left edge, at the axis and at the right edge of the embankment, respectively. Details of all the monitoring instruments used and the dates of the staged construction are given in the [OnlineSupplement](#). The waiting period between two stages was either 2 months or until stabilization of the measurements from all monitoring instruments.

Table 2 includes the calculated settlements at the embankment axis and the measurements from the three devices. Calculated settlements are consistently bigger than measurements. The overprediction trend decreases at each subsequent stage from 276% to 42%.

The comparison of measured and calculated settlement values as a function of time is shown in Figure 2. More specifically, Figure 2 shows a) embankment height vs. time from the start of construction b) settlement data provided by the Contractor vs. time from the start of construction for settlement gauges ST10.2, ST11.2, and ST12.2 and c) estimated settlement-time curves derived from the pertinent geotechnical calculations for the four construction stages in Table 2. (i.e. for embankment heights of 4.0 m, 8.0 m, 11.5 m, and for the final height of 12.3 m or 13.3 m with the surcharge).

It should be noted that in the settlement diagram of Figure 2, the depicted blue curve is theoretical and has been derived by combining the individual calculated settlement vs. time curves, each one corresponding to the intermediate embankment heights. The settlement calculations, in terms of time, were made taking into account the actual length of the installed prefabricated wick drains (based on the data provided by the Contractor), which for the examined section is the same with the proposed length

of the geotechnical study and equal to 20 m. The "beginning" of time in the theoretical blue curve is indicative and was selected to correspond to the time of imposition of the full embankment load of the first construction stage. The superposition of the individual curves (dashed blue lines) is also indicative to show the transition to the successive theoretical calculation curves of each intermediate stage.

Table 1. Calculated settlement values at the cross section 195

Constru- ction stage	Embank- ment height	Embankment geometry		Influ- ence depth	Calculated settlements at the embankment axis (cm)					
		Base width, A ₁ (m)	Crest width, A ₀ (m)		(m)	Consolidation settlement per layer, S _{cons}				Total
	Simmed.			Layer		S _{cons, i}	S _{cons, i} / S _{cons, tot} (%)	S _{cons, tot}		
1 st	4.0	46.7	41.3	28.4	3.2	Ia	34.9	65.1	53.6	56.8
						II	10.8	20.1		
						IIIa	0.0	0.0		
						II	2.1	3.8		
						IVa	5.3	9.9		
						IVb	0.6	1.0		
2 nd	8.0	46.7	35.8	42.8	9.6	Ia	50.3	57.3	87.8	97.4
						II	18.0	20.5		
						IIIa	0.0	0.0		
						II	3.9	4.4		
						IVa	13.8	15.7		
						IVb	1.9	2.1		
3 rd	11.5	46.7	31.0	50.8	13.9	Ia	59.2	53.5	110.7	124.6
						II	22.5	20.4		
						IIIa	0.0	0.0		
						II	5.1	4.6		
						IVa	19.6	17.7		
						IVb	4.3	3.8		
Final	12.3 plus surcharge of 1.0m	46.7	30.0	52.5	15.9	Ia	60.8	51.5	118.0	133.9
						II	23.9	20.3		
						IIIa	0.0	0.0		
						II	5.5	4.7		
						IVa	21.9	18.6		
						IVb	5.9	5.0		

Table 2. Comparison of calculated and measured settlement values at cross section 195 at the end of each construction stage

Construction stage	Embankment height (m)	Duration (from start of construction) (days)	Calculated settlements at the embankment axis (cm)			Measured settlements (cm)		
			Immediate	Consolidation	Total	ST10.2 left	ST11.2 axis	ST12.2 right
1 st	4.0	88	3.2	53.6	56.8	15.8	15.1	16.0
2 nd	8.0	161	9.6	87.8	97.4	42.2	46.6	43.4
3 rd	11.5	245	13.9	110.7	124.6	69.9	73.0	72.7
Final	12.3 plus surcharge of 1.0m	406	15.9	118.0	133.9	92.3	94.4	90.7

Figure 2 shows that toward the end of each construction stage, measured settlements have almost stabilized. Stabilization of settlements and measured settlements not exceeding calculated values were the two criteria to proceed to the next construction stage. The evolution of settlement with time shows again that the discrepancy between measured and calculated values is more pronounced at the early construction stages and becomes less significant when reaching the final stage of construction.

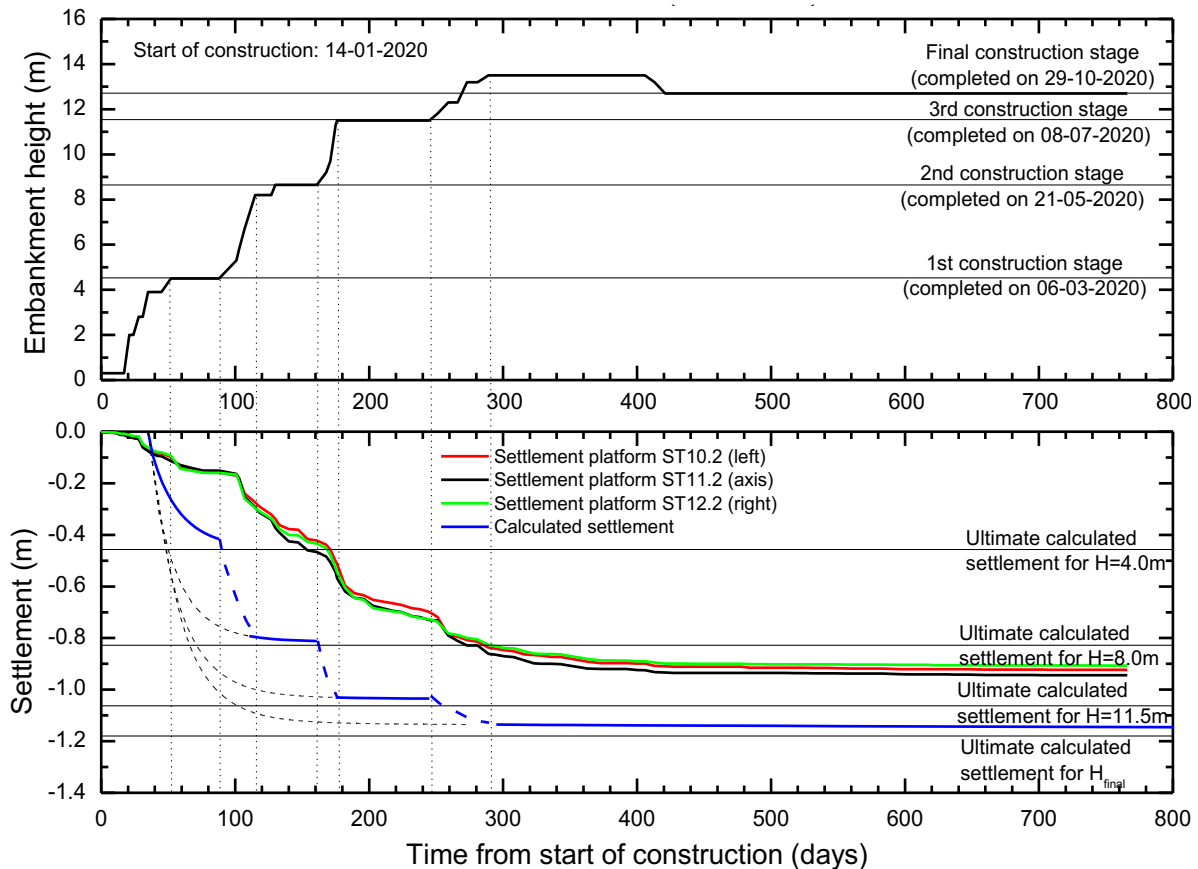


Figure 2. Progression of embankment height, calculated and measured settlements at cross section 195

Table 3 shows measured vs. calculated settlements at all nine sections of the main branch of the motorway embankment. Calculated settlements again are higher. The last column of Table 3 includes the overprediction, computed as $(\text{calculated value} - \text{measured value}) / (\text{measured value})$ and found to vary from 36% to 207%. The highest overpredictions occur at the two shortest embankments (cross section 79, height: 4.10 m; cross section 301, height: 6.30 m).

4.4 Discussion

Differences between measured and calculated settlements raise two issues for discussion in the classroom (and beyond). The first issue is where should we look for reasons for the differences and what—hypothetically or realistically—could we have done differently. Reasons may concern calculation methods, soil profile and soil parameters. An improvement of the calculation methods is to consider two-dimensional consolidation, but this is not expected to result in large reduction of settlement. Another improvement concerns considering a stress distribution produced by methods better suited for the project soils, i.e. not from elasticity assuming a uniform profile. Again, this is not expected to make a big difference. In fact, for weaker surficial soils, under the embankment axis it would produce larger increases of effective stress (but smaller increases under the toe) and, hence, even larger settlements. A third possibility that combines geometry and stress distributions may be more germane to the specific case study, which deviates from plane strain, is to account for the three-dimensional effects related to how the embankment was actually constructed. In reality, the embankment length is limited, especially

at the early stages of the construction, depending on the requirements of the construction site. The embankment has a total length of 1.5 km, but it is interrupted by two bridges, where the interchange goes over the motorway, between cross sections 157(T1) and 185, and over the railroad, between cross sections 239(T3) and 264(T4) (see [OnlineSupplement](#), e.g. Figures S6, S12, S13, S14). Cross section 195, almost 50 m wide, is at a distance of 80 m from the 90-m long bridge going over the motorway and 240 m from the 75-m long bridge going over the railroad. This is another reason why cross section 195 was selected for this case study (in addition to the significant thickness of the underlying silty-clayey layers already mentioned), instead of cross section 239(T3), where the embankment is highest (14.2 m), which is only 20 m away from the bridge going over the railroad.

Table 3. Calculated and measured settlements at nine cross sections of the 1.5-km long embankment

Measure- ment device code	Cross section	Chainage	Position of measurement device	Embank- ment height (m)	Settlement values (cm)		Over- prediction
					Measured	Calculated	
M2270	79	2+270	axis	4.10	21.0	64.5	207%
ST1			left		66.7		
ST2	129	2+520	axis	8.0	75.9	113.8	50%
ST3			right		64.5		
ST4			left		62.0		
ST5	157 (T1)	2+664	axis	10.10	81.5	134.4	65%
ST6			right		65.6		
ST7.2			left		81.7		
ST8.2	185	2+800	axis	12.5	87.7	136.7	56%
ST9.2			right		84.1		
ST10.2			left		92.3		
ST11.2	195 (T2)	2+850	axis	12.30	94.4	134	42%
ST12.2			right		90.7		
ST16			left		89.5		
ST17	239 (T3)	3+070	axis	14.20	102.2	147.4	44%
ST18			right		115.0		
ST19			left		122.9		
ST20	264 (T4)	3+195	axis	13.80	118.1	160.6	36%
ST21			right		94.3		
ST22			left		57.9		
ST23	283	3+290	axis	10.50	53.5	124	132%
ST24			right		54.6		
ST25			left		27.4		
ST26	301	3+380	axis	6.30	29.3	81.5	178%
ST27			right		25.2		

Discrepancies in geotechnical projects are customarily and vaguely explained with soil heterogeneity and uncertainty caused by not having a borehole close to the cross section where the calculation is made. This would be relevant if both underpredictions and overpredictions were observed. Herein, the systematic overprediction precludes that heterogeneity and uncertainty are the main culprits by themselves. One reason already mentioned –related to heterogeneity– for a systematic overprediction is the choice to “err on the clay side” and ignore occurrences of small-thickness sandy layers within the

finned-grained layers I,II, IV and V in the design soil profile. The fact that the two shortest embankment cross sections have the largest overpredictions draws attention to the soils closer to the surface, which are responsible for the highest percentage of settlement. Although the depositional history of the site justifies a normally consolidated soil, as was assumed to be the case for surficial layer I, aging can produce an apparent preconsolidation pressure, also mentioned by Karstunen et al. (2020) as cause of overpredicting settlements of soft clays (if ignored). Fluctuations of the water table may have also created a surficial crust that is not accounted for in the design soil profile. A final hypothesis explaining the lower displacements measured for the short embankment sections is related to potential sparse lenses of lightly expansive clays, responsible for swelling stresses measured in laboratory tests in the range of 10-55 kPa. There may be a downward displacement of the low embankments, when the foundation clays undergo temporary desiccation. During the rainy season, the desiccated clay may partly swell and the settlement effect is reversed.

The second issue is what differences between observed and predicted settlements are recorded in actual projects. Without published numbers from real projects, the next best option is large-scale instrumented tests combined with prediction competitions, which is the approach Karstunen et al. (2020) followed in their class project. According to the data they used, predictions by professionals varied from 61% underprediction to 69% overprediction.

5 Concluding remarks

This paper selected aspects of a motorway embankment case study that are suitable for instruction even in an introductory soil mechanics course, either for a lecture presentation, or for an assignment, or for both. In the context of an assignment with given soil profile and design parameters, students can readily calculate one-dimensional consolidation settlements for a succession of silt and clay layers separated by sand and gravel layers and compare them with measured values. Then, the instructor can comment on the good comparison of the numbers calculated by the students and those in the project report. The large magnitude of measured and calculated settlement is an opportunity to connect geology and resulting soil profile and parameters. It is fortuitous that the project location is very close to the Thermopylae Pass (the place of the battle between Persians and Ancient Greeks) known world-wide for its morphology (pass), which has changed beyond recognition in the last 2500 years due to the same sedimentation processes that created the deep soil deposits underneath the motorway embankment. The instructor can also show to the students comparisons of measured settlement to settlement predictions made by other students and by practitioners. The comparison of calculated and measured settlements is an opportunity to introduce the students to the variability expected in real projects and dispel the notion of the geotechnical engineer attempting to calculate the one correct value, as many students are led to believe by solving problems with the specific method taught in class and the specific parameters given in the problems.

What is more, this case study raises questions suitable for discussion beyond the classroom. Two such types of questions are identified. One question concerns the chosen calculation method. The systematic overprediction of the settlements suggests that a systematic element of soil behavior may have been misrepresented, e.g. the potential of the shallow clay layers exhibiting an overconsolidated-type behavior. A second question –of much broader relevance– concerns the expected variation between calculated and measured values in practice. Published ranges of differences between calculations and measurements are typically obtained from prediction competitions where practitioners and researchers are invited to predict the behavior (e.g. settlement or ultimate bearing load) of a testing facility. These results may not be representative of the ranges expected in real projects, where the stakes are higher than in competitions. This observation underscores the value of practitioners publishing results comparing calculations and measurements from real projects.

Acknowledgements

The first author acknowledges the input of Mr. Apostolos Ritsos and Dr. Anastasios Kollios during the preparation of the project report. Both authors thank them and Prof. Achilleas Papadimitriou for their input for the discussion on the discrepancies between calculated and measured settlements and thank TERNA SA for the permission to publish materials from the project.

References

- Ambrose, S.A., Bridges, M.W., DiPietro, M., Lovett, M.C., Norman, M.K. (2010). *How Learning Works: 7 Researched-based Principles for Smart Teaching*, Jossey-Bass, San Francisco, USA.
- Barnes, G.E. (2005). *Soil Mechanics-Principles and Practice*, Palgrave Macmillan Edition, Houndmills, Basingstoke, Hampshire, UK.
- Karstunen, M., Birmpilis, G., Dijkstra, J. (2020). Developing Soft Soil Engineering Skills Using “Class B” and “Class C” Predictions, *Proceedings ISSMGE Int. Conf. on Geotechnical Engineering Education GEE2020*, Pantazidou, M., Calvello, M. & Pinho-Lopes, M. (Eds), Athens, Greece, June 23-25, pp. 38-50.
- Marinos, V. (2025). Personal Communication.
- Orr, T.L.L., Pantazidou, M. (2013). Case Studies Used in Instruction to Achieve Specific Learning Outcomes: The Case of the Embankments Constructed for the Approach to Limerick Tunnel, Ireland, Paper No 1.15b, 7th Int. Conf. on Case Histories in Geotechnical Engineering, Chicago, USA, May 1-4, <https://scholarsmine.mst.edu/icchge/7icchge/session01/13/>
- Ostergerg, J.O. (1957). Influence Values for Vertical Stresses in a Semi-infinite Mass due to an Embankment Loading, *Proceedings of 4th Int. Conf. Soil Mechanics and Foundation Engineering*, London, Aug. 12-14, Butterworths Publications Ltd, London, UK, pp. 393-394.
- Pantazidou, M., Koutsoyiannis, D., Saroglou, C., Marinos V., Iliopoulou, T. (2021). Infuse Teaching with Research Practices: A Pilot Project – Welcome Presentation for First-Year Students on Time Scales in Civil Engineering Projects, “The Role of Education for Civil Engineers in the Implementation of the SDGs”, 1st Joint Conference of EUCEET and AECEF, Thessaloniki, Greece, November 12.
- Pechlivanidou, S., Vouvalidis, K., Løvlie, R., Nesje, A., Albanakis, K., Pennos, C., Syrides, G., Cowie, P., Gawthorpe, R. (2014). A Multi-Proxy Approach to Reconstructing Sedimentary Environments from the Sperchios Delta, Greece. *The Holocene*, 24(12), pp. 1825-1839. <https://doi.org/10.1177/0959683614551219>
- Salgado, R. (2007). *The Engineering of Foundations*, Intern. Edition, McGraw-Hill, Boston, USA.
- Vouvalidis, K., Syrides, G., Pavlopoulos, K., Pechlivanidou, S., Tsourlos, P., Papakonstantinou, M. F. (2010). Palaeogeographical Reconstruction of the Battle Terrain in Ancient Thermopylae, Greece. *Geodinamica Acta*, 23(5–6), pp 241–253. <https://doi.org/10.3166/ga.23.241-253>
- Xenaki, V., Doulis, G., Athanasopoulos, G. (2016). Geotechnical Design of Embankment: Slope Stability Analyses and Settlement Calculations. *International Journal of Geoengineering Case histories*, 3(4), pp.246-261. doi: 10.4417/IJGCH-03-04-04

Authors’ bios

Valia Xenaki, Edafomichaniki S.A., Athens (Greece)

Valia Xenaki is a Civil Engineer, holder of an MSc and PhD with specialty in Soil Mechanics. She is a Senior Geotechnical Engineer at Edafomichaniki S.A., Athens, Greece, with over 20 years of experience on a wide range of consulting projects focusing on the fields of geotechnical engineering. Consulting projects have involved the design, modeling/analysis, monitoring and construction of a number of projects in Greece. She is author of 25 publications all of which on geotechnical engineering topics and two of them on geotechnical engineering education topics. She is a member of the ISSMGE Technical Committee TC306 on Geo-engineering Education since 2018.

Marina Pantazidou, National Technical University of Athens (Greece)

Marina Pantazidou is an associate professor at the Civil Engineering School of the National Technical University of Athens, Greece. Apart from university appointments in the US and Greece, her professional experience also includes work in hazardous waste consulting. Her research topics are drawn from environmental geotechnics and engineering education. She is author of 100 publications, 25 of which on geotechnical engineering education topics. She has been a guest editor for two special issues on

geotechnical engineering education, one on case studies developed for geotechnical engineering instruction. She has been actively involved with the Hellenic Society for Soil Mechanics and Geotechnical Engineering (secretary general 2012-2015 and board member 2015 -) and the ISSMGE Technical Committee TC306 on Geo-engineering Education (core member 2010-2013, vice chair 2013-2017, chair 2017 -). She chaired the ISSMGE Int. Conf. on Geotechnical Engineering Education GEE2020, (streamed from) Athens, Greece, June 23-25.

Applications of ICT Tools

Enhancing geotechnical site investigation and project-based education through virtual reality: the GeoSim experience

A. Abdallah, O. Cuisinier & F. Masrouri

LEMTA - ENSG - Université de Lorraine, Nancy, France

adel.abdallah@univ-lorraine.fr, olivier.cuisinier@univ-lorraine.fr, farimah.masrouri@univ-lorraine.fr

ABSTRACT: This paper presents GeoSim, a virtual reality (VR) tool designed to enhance geotechnical site investigation and project-based education. GeoSim offers an immersive experience, allowing engineering students to be immersed into a real-world site investigation project for a building construction. They can optionally access short but engaging multimedia educational materials as reminders of the general approach and usual testing methods. By addressing the limitations of traditional teaching methods, GeoSim provides a cost-effective and logistically feasible alternative. Allowing students to iteratively change their initial choices and progressively improve their ground model, is a key feature for developing their decision-making skills. GeoSim integration in the project-based learning activities is expected to significantly enhance students' understanding and application of site investigation process, making it a valuable resource for geotechnical engineering education.

Keywords: *Virtual reality, Site investigation, Project-based, In situ tests, Laboratory tests*

1 Introduction

Geotechnical site investigation is crucial for ensuring the safety and durability of built structures. Traditional teaching methods, which focus on theoretical aspects, must be complemented by project-based activities to develop and assess engineering students' skills. These activities help students make informed choices about selecting laboratory and in situ testing methods, and designing and positioning coring and testing on construction sites. Training geotechnical engineering students in site investigation practices is essential for balancing risk assessment and mitigation with project cost reduction. However, the equipment and maintenance required for geotechnical in situ testing often exceed the available funding of educational institutions. Consequently, teaching teams resort to simplified equipment for practical work, which remains costly and complicated to organize, and depends on weather conditions and site accessibility. Partner companies sometimes organize on-site demonstrations, but these are also complex to arrange and depend on teaching schedules, company workloads, and site accessibility.

Recent advancements in Virtual Reality (VR) technology and availability of adapted hardware solutions offer a promising solution for engineering education. Oje et al. (2003) provided a comprehensive review on VR-assisted engineering education covering a wide variety of applications and discussing benefits and shortcomings. They reported that most applications focused on aesthetic and attractiveness of VR technology, and suggest that future developments should consider learning efficiency through empirically tested learning theories.

GeoSim, an artificial environment simulating a real-world construction site for an industrial building, is developed to address these challenges specifically in geotechnical investigation design. GeoSim can be used with a standard VR headset or on a PC, tablet, or smartphone. It is intended to provide geotechnical engineering students with an immersive experience into the design and processing of a site investigation project.

2 Current practice in Geotechnical Engineering courses

The geotechnical engineering curriculum at Université de Lorraine - ENSG combines theoretical courses with practical learning units as summarized in Table 1. One of these practical units focuses on experimental soil mechanics, allowing students to practice current soil identification and testing methods. Whenever possible, visits to construction sites and demonstrations of in situ geotechnical tests are organized with the support of partner companies. In the learning units dedicated to geotechnical design and stability analysis (including foundations, tunnels, retaining structures, and slope stability), project-based learning activities complement the theoretical courses. During these activities, students are provided with soil properties data and tasked with designing projects. Professors are often asked to explain how the data was obtained and how site investigations are conducted, relying on theoretical considerations and selected case studies to address these questions.

Table 1. Learning units of the geotechnical engineering specialization curriculum at Université de Lorraine - ENSG

Semester	Theory courses	Practice and Design-Oriented courses
1	Soil mechanics (40h) Rock mechanics (24h)	Experimental soil mechanics (24h) Shallow and deep foundations (24h) Slope stability and retaining structures (24h) Tunnels and underground structures (24h) Environmental geotechnics (24h) Geology/Geotechnical field work (2 weeks)
2	Advanced soil & rock Mechanics (24h)	Foundations and retaining structures (24h) Tunnels and underground structures (24h) Soil dynamics, vibration and earthquake analysis (24h) Energy Geotechnics (24h) Natural hazards management (24h) Linear infrastructures (24h) Geotechnical structures design (24h) Geophysics applied to civil engineering (24h) Construction site management (24h)

Developing students' skills for site investigation, requires repeated experiences covering the variety of site and project configurations. Engaging the students in the whole process of defining and interpreting the reconnaissance operations, and going a step further to designing the project. Repeated practice iterative feedback/improvement sequences, is undeniably the best way to measure the consequences of the choices the engineers can make when selecting testing methods and positioning boreholes. Putting such activities is highly resource-consuming and doesn't generally align with faculty and equipment availability. Developing VR-based tools is an interesting solution matching site investigation learning outcomes with logistical and financial support in universities.

3 Virtual Reality in Education

Oje et al. (2023) reviewed the educational uses of VR technologies distinguishing non-immersive and immersive technologies. They pointed out that in the engineering education, students frequently face the difficulty of understanding abstract concepts and visualising complicated 3D configurations, and non-immersive VR technologies are very helpful to clarify these concepts and configurations while immersive VR adds a higher degree of interaction for a more-realistic experience.

Immersive technologies offer interesting opportunities in the civil and geotechnical engineering education context. 360-cameras are able to capture a view covering an entire sphere by assembling the views taken by two half-sphere lenses (forward and backward). Software tools allow then to reconstruct the 3D-view of the captured scene. The end-user can be immersed into the reconstructed environment using a VR-headset or simply on a screen of a personal computer, a tablet or a smartphone. 3D-displacements and rotations are possible and allow the user to evolve in the VR-environment. Additional

multimedia materials (photos, videos, text and sounds) can be also added to enrich the user experience and offer interaction possibilities. The use of a VR headset is a way more immersive experience than a computer/tablet/smartphone flat screen that necessitates actions from the user to interact with the environment. Simple VR goggles can however be used for a low-cost enhanced immersive experience.

Jaksa (2020) reported that these technologies are used at the University of Adelaide (Australia), for offering virtual visits to various civil engineering construction activities to the students providing them with a wide variety of learning experiences. In particular, an educational project reconstructed three distant multi-storey building and introduced for the convenience of the users a 'teleport' function in the simulation, avoiding long and uninteresting walking sequences when moving from one building to another. Fernandez et al. (2023) developed a virtual experience of a drilling work where the user is asked to perform drilling and extracting the soil coring following instructions given by a virtual supervisor with a focus on safety and risk prevention. The simulator was built in a videogame development environment, from 3D models of the geotechnical drilling machine and a realistic construction site environment, and scenarios of inventoried interaction possibilities. Afsharipour and Maghoul (2023) explored application of VR and Augmented Reality (AR) to enhance teaching geotechnical concepts. They developed 3D modelling and animation models for soil phase diagram, Consolidated Undrained (CU) and Consolidated Drained (CD) triaxial tests, direct shear test, hydrometer tests and Mohr-Coulomb failure criterion. It is worth noticing that VR and AR technologies are having expanding application in corporate training. In The geotechnical field, this use includes training in safety and risk mitigation on construction sites, and training on the use of sophisticated machinery such as TBM (Tunnel Boring Machine). However, little feedback from geotechnical companies on the specific added-value is available in the scientific literature. Martins et al. (2021) made a literature review on VR/AR use in corporate training report that the technology is clearly maturing but depending on the digital skill level of the target audience. They recommend incorporating artificial intelligence to enhance coaching of trainees to proactively optimize tasks accomplishment.

The most challenging aspect of using VR technologies in education in general and in geotechnical engineering in particular, is aligning the VR experience with the learning outcomes (Ghazali et al., 2024). This aspect is decisive in the student's perception of the VR activity experience. A well-designed realistic scenario allowing for iterative improvement is central for skills' development assessment. Additionally, the health issues have to be considered when designing VR experiences (Ghazali et al., 2024). The most serious issue is the cybersickness induced by the contradictory perceptions by the central nervous system detecting movement and the vestibular system not detecting it. Precautionary recommendations include shortening the VR sessions and adapting their duration to the specifications of the head-mounted devices eventually used.

4 The GeoSim project

4.1. Construction site and project presentation

The selected construction site is located in the "La ferme de La Bouzule" experimental domain owned by the Engineering School of Agronomy and Food Science (ENSAIA), of the Université de Lorraine. It is situated 12 km North-East of Nancy (Figure 1). The projected construction is an administrative/industrial annex three-storey building covering a 20mx15m surface. The structure of the building comprises two lateral load-bearing walls and 11 columns (Figure 2). Table 2 summarises the design load takedowns of the building. The student's ultimate task is to design the foundations of all structural elements of the building based on the geotechnical site investigation program they will have to define.

Based on the desk study, the soil was expected to comprise a surface layer of clayey silt of 3 to 6 m thickness upon a thick clay substratum. The water table depth was expected to be reached between 2 and 3 m depth. A real investigation program was conducted to provide reference experimental data for GeoSim. This program included: (i) one pressuremeter test with maximum depth of 6 m; (ii) dynamic penetrometer test to a 6 m depth; (iii) soil cuttings and cores collection for laboratory tests; (iv) complete set of laboratory tests. The two boreholes were driven in two distant positions on the surface covered by the project. Some additional tests were available from previous boreholes made in the vicinity of the site. The relatively simple geology in the site, allowed to accurately define a ground model up to 15 m

depth confirming the presence of a 4m-thick clayey silt layer and a clay substratum down to 15+ m. the water table depth was around 2.5 m.



Figure 1. Construction site location with the projected building location (blue square)

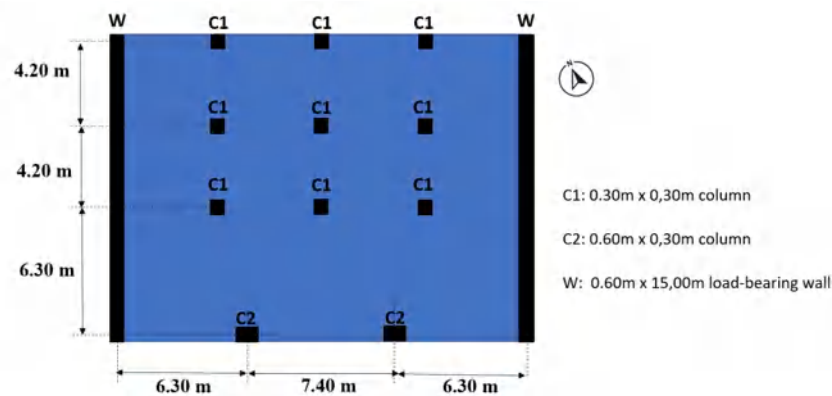


Figure 2. Drawing of the structural elements of the projected building: C1 and C2 stand for square and rectangular columns respectively, and W represents the load-bearing walls

Table 2. Load takedowns of structural elements of the projected building

Structural element	Permanent vertical load	Variable vertical load
W load-bearing wall	120 kN/m	80 kN/m
C1 column	230 kN	94 kN
C2 column	360 kN	108 kN

4.2. Video and photo shooting

Multiple video and photo shooting sessions were necessary to assemble the needed resources for GeoSim Development. In particular, a one-day session was organized with the support from Géotec® Group, a leading consultancy in geotechnical engineering who deployed two drilling machines, testing equipment with one senior engineer and two technical staff members. One 360-camera (Insta360® Pro2) was used for capturing the 3D views of the site and the drilling machinery. Figure 3 shows some photos from the shooting sessions.



Figure 3. Photos from the shooting sessions (top : in situ test and bottom : laboratory tests)

4.3. Additional educational resources

One five-minute video is dedicated to presenting the general process of geotechnical site investigations combining sequences illustrating the desk study, site visit and machinery setting. Seven two-minute videos are focused on laboratory testing (soil identification tests, oedometer, shear box and triaxial) and in situ test (dynamic penetrometer, cone penetration and pressuremeter). Lecture notes, links to websites and other course materials are also made available. For capturing 2D video sequences, the Panasonic® GH5s camera was used. Photo and video editing were made using Adobe® Photoshop and Premiere, while Unity® software was used for creating the VR environment. The last was selected in particular for its advanced functionalities permitting to introduce interactivity to the 360°-scene with clickable buttons and elements and incrusting images and videos.

4.4. Scenario implementation

GeoSim is designed as a learning platform featuring four modules as shown in Figure 4. The primary objective is to provide the user with a standard pathway simulating the different phases of a real-world site geotechnical investigation for an administrative/industrial three-storey building construction project. The secondary objective is to deliver as an option to users, a complementary training on the general methodology for setting up a geotechnical site investigation, including multimedia documents combining slide presentations, text documents, videos and interviews, to introduce/remind the general approach of setting boreholes and the most frequently used testing methods. Figure 5 shows the Moodle LMS (Learning Management System) space dedicated to the material library. The user can navigate forth and back to these learning materials from any module.

5 GeoSim in practice

GeoSim's standard pathway starts in a virtual meeting room, with a welcome message and a presentation of the project specifications given by a virtual representative of the project owner (Figure 6). Architectural drawings and load takedowns for the projected building along with the local geological/topographic maps, precise location and aerial photo of the site are provided. At this stage, the user is asked to carry on a desk study, including searching for any available additional data which

could be useful for the project. The overall geological configuration should be estimated and used to preconfigure the relevant investigations.

Afterwards, the user is ‘teleported’ to the virtual site for a site visit. They can visit the site and note any useful particularity, check the access of the testing machinery, make GPS position measurements to calculate distances and level differences, and stake borehole locations. For each stake, They are asked to define the maximum depth of investigation, and to choose the testing methods including in situ tests (pressuremeter, dynamic penetrometer, cone penetration tests) and/or laboratory tests (geotechnical identification: grain-size distribution, water content and bulk density, Atterberg limits, methylene blue test, compaction curve, CBR; oedometer test; shear box or triaxial shear strength parameters). In order to raise the student awareness of the financial aspects of the investigation, the platform shows the estimated cost of the selected tests.

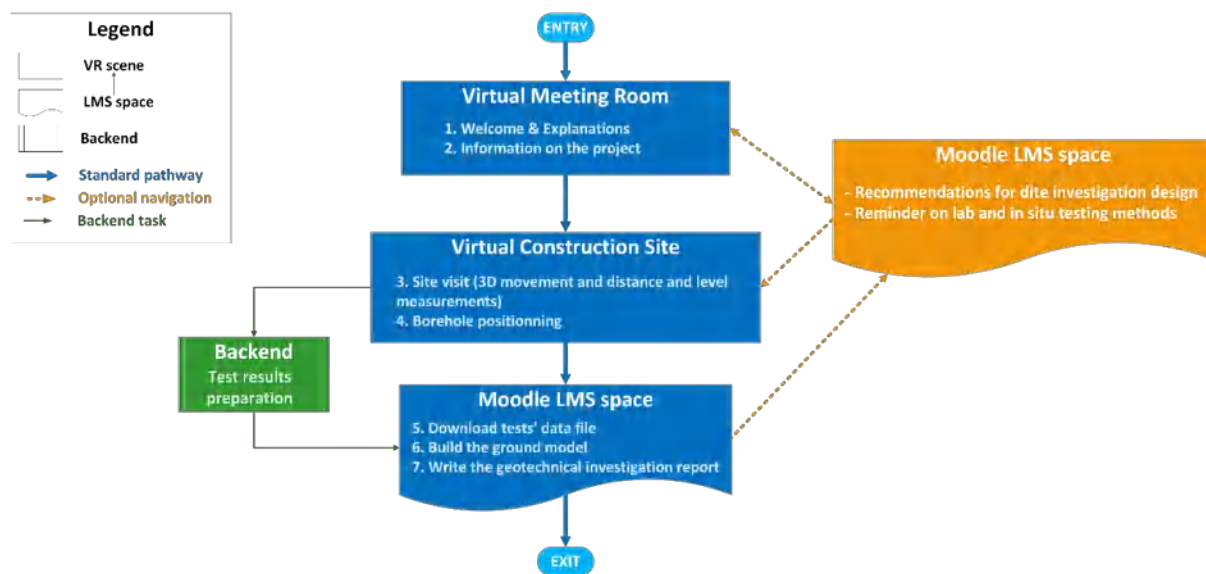


Figure 4. Workflow of the GeoSim project storyboard

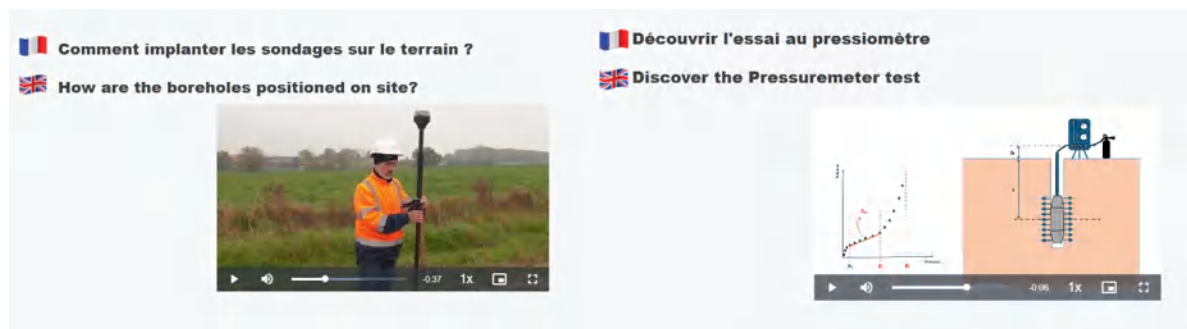


Figure 5. Optional educational resources frontend in the Moodle LMS space (right: sitting of the boreholes and left: pressuremeter test presentation)

Based on the available results from real in situ and laboratory tests, the professors generate in the backend, the data in accordance with the student ordering. These data are generated by introducing some random noise consistently with the observed variability.

Subsequently, the user is guided to the Moodle LMS space to retrieve the results of the ordered investigation campaign. He/she is invited to check the data, to point out any inconsistency and to make the necessary interpretation to define the ground model attributing values to the design parameters for each soil layer. This final phase ends up with uploading a complete geotechnical investigation report on the Moodle LMS space to be evaluated by the professors. Once the feedback is given, the student can eventually repeat the whole process to improve the site investigations.

To engage students and enhance their skills in designing optimized site investigations, they are encouraged to iterate the process by varying the number and types of investigation points. For instance, students might start with three boreholes and two types of tests, then adjust to four boreholes and three types of tests based on initial findings. This approach helps develop an awareness of the importance of balancing the quantity of boreholes and tests with the required accuracy for the project at hand, while also controlling the cost of the reconnaissance.



Figure 6. Screenshot from the simulation showing the virtual meeting room during project introduction

6 Future developments

GeoSim was designed as a prototype to demonstrate the feasibility and effectiveness of the concept. An enhanced version is planned, and further development perspectives include but aren't limited to:

- Adding growing complexity geological/geotechnical complexity;
- Adding different types of construction projects, in particular, linear projects as roads, railways, embankments and tunnels;
- Incorporating a built-in data generation module which will automatically generate test results considering lithology and soil parameters variability in accordance with the settings specified by the professors.

The effort needed to enrich GeoSim with additional sites of increased complexity, and to include new construction projects beyond foundation design, such as embankments, slope stability, and retaining structures, is relatively moderate. The resources library is quite complete; only the project material needs to be developed, and the data generation module must be updated to handle the new lithology.

7 Conclusion

In this paper, the GeoSim simulator concept, objectives, development steps and expectations in terms of future usefulness as an educational resource were presented. This tool is dedicated to enhance teaching geotechnical site investigation to engineering students.

The first objective was to develop several resources to be used as educational material for teaching geotechnical routine testing methods. The second objective was to develop a VR tool to simulate a real-world investigation project for the construction of a building. The chosen scenario for this tool was to allow the students to iteratively sharpen their knowledge and develop their skills in choosing the appropriate number of boreholes and the useful testing methods, to properly define the ground model for the foundation design while optimising the investigation cost. This project is a prototype that can be

enriched with moderate efforts, to include new sites and new construction projects with increased complexity.

At the moment of writing the manuscript, the project was not finished and the development phase is scheduled to end in June 2025. The final product will be shared to everyone who might be interested in trying and using it under a Creative Commons (CC) open licence. The main language is French but text translations and video subtitling in English will be systematically added.

Acknowledgements

The authors acknowledge the financial support from the French Research Agency (ANR) in the framework of PLEIADES project under the grant reference ANR-21-DMES-0010. They highly appreciate the invaluable technical and conceptual support in designing and developing the simulator, provided by the “audio-visual” team from the Digital Service of Université de Lorraine.

They also acknowledge the important support from Géotec® Group teams, and appreciate the access given to the site by Université de Lorraine - ENSAIA.

References

- Afsharipour, M., Maghoul, P. (2023). Towards Education 4.0 in Geotechnical Engineering Using a Virtual Reality/Augmented Reality Visualization Platform. *Geotech Geol Eng* 42, 2657–2673.
- Fernandez, A., Munoz-La Rivera, F., Mora-Serrano, J. (2023). Virtual Reality Training for Occupational Risk Prevention: Application Case in Geotechnical Drilling Works. *International Journal of Computational Methods and Experimental Measurements*, Vol. 11, No. 1, pp. 55-63. <https://doi.org/10.18280/ijcmem.110107>.
- Ghazali, A. K., Ab. Aziz, N. A., Ab. Aziz, K., Kian T. S. (2024). The usage of virtual reality in engineering education, *Cogent Education*, 11:1, 2319441, DOI: 10.1080/2331186X.2024.2319441.
- Jaksa, M. B. (2020). Reflections on Some Contemporary Aspects of Geotechnical Engineering Education – From Critical State to Virtual Immersion. *Proceedings of the online International Conference on Geotechnical Engineering Education (GEE2020)*, Editors: Marina Pantazidou, Michele Calvello and Margarida Pinho Lopes.
- Martins, B. R., Jorge, J. A., Zorzal, E. R. (2021). Towards augmented reality for corporate training. *Interactive Learning Environments*, vol. 31 - issue 4. <https://doi.org/10.1080/10494820.2021.1879872>.
- Oje, A. V., Hunsu, N. J., May, D. (2023). Virtual reality assisted engineering education: A multimedia learning perspective. *Computers & Education: X Reality*, Vol. 3, 100033. <https://doi.org/10.1016/j.cexr.2023.100033>.

Authors' bios

Adel Abdallah, ENSG, Université de Lorraine, Nancy, France

Dr. Adel ABDALLAH is an Associate Professor of Geotechnical Engineering at Nancy Engineering School of Geology, Université de Lorraine, France, since 2000. He holds a Civil Engineering BEng from ENI Gabès, Tunisia (1993), a MSc in Civil and Mining Engineering (1995), and a PhD in Geotechnical Engineering (1999) from Lorraine's National Polytechnical Institute in Nancy, France. His research is focused on coupled THM behaviour of natural, compacted and treated soils. He is particularly interested in numerical modelling and model parameter calibration, and in applications of machine learning and artificial intelligence in Geotechnical Engineering. He teaches soils mechanics at graduate and undergraduate levels, numerical modelling, geotechnical design and machine learning. He served as the Academic Dean of his Engineering school from 2012 to 2018.

Olivier Cuisinier, ENSG, Université de Lorraine, Nancy, France

Prof. Olivier CUISINIER is Professor of Geotechnical Engineering at Nancy Engineering School of Geology, Université de Lorraine, France, since 2008. He earned his PhD from the Université de Lorraine in 2002 before joining the Laboratoire Central des Ponts et Chaussées (LCPC) as a Researcher, where he worked until 2008. That year, he transitioned to academia as an Associate Professor at the Université de Lorraine, and in 2020, he was promoted to Professor of Geotechnical Engineering. Dr. Cuisinier's research focuses on the fundamental behavior of soils and the advanced laboratory characterization of fine-grained soils. With nearly 20 years of experience in soil mechanics, his expertise covers unsaturated expansive soils, naturally and artificially cemented soils, with a particular emphasis on their long-term behavior. Beyond his research, Dr. Cuisinier actively contributes to the geotechnical community. He serves since 2024 as the Chair of the Scientific Committee of the French Association for Soil Mechanics and Geotechnical Engineering.

Farimah Masrouri, ENSG, Université de Lorraine, Nancy, France

Prof. Farimah Masrouri holds a doctorate in Geotechnics and Civil Engineering from INSA de Lyon, as well as a Habilitation à Diriger des Recherches (HDR) from the Institut National Polytechnique de Lorraine. She is currently a Professor at the University of Lorraine, École Nationale Supérieure de Géologie in Nancy, France, where she teaches both theoretical and applied soil mechanics, geotechnics, and the modeling of thermo-hydro-mechanical behavior in saturated and unsaturated soils, alongside structural design and natural risk management. Her research primarily focuses on the multiphysical and multiscale behavior of saturated and unsaturated clayey soils. This research approach integrates micro- and macroscopic properties with chemo-thermo-hydro-mechanical behavior, as well as phenomena related to time and durability. The applications of her work span various structures, including the storage of high, medium, and low-level radioactive waste, energy geostructures, shallow and deep foundations, retaining walls, and embankments. Since 2007, she has been an active member of the International Society for Soil Mechanics and Geotechnical Engineering, participating in the activities of three international technical committees: 106 (Unsaturated Soils), 306 (Geo-engineering Education), and 308 (Geo-Energy).

Implementation of a blended learning strategy for geotechnical courses

L. Araújo Santos¹, V. Ribeiro² & S. Proença³

¹ Polytechnic University of Coimbra, SUScita, Coimbra, Portugal
lmsantos@isec.pt

² Higher Institute of Educational Sciences, CI ISCE – Research Centre, Penafiel, Portugal
veraribeiro@esec.pt

³ Polytechnic University of Coimbra, CERNAS, Coimbra, Portugal
sproenca@esac.pt

ABSTRACT: Higher education learning environments have transformed significantly over the past few decades. While traditional lectures remain prevalent in theoretical courses, creating varied learning methods that resonate with the newer generation of students, particularly those who have experienced post-COVID-19 education, is crucial. To tackle student motivation and attention issues, the flipped learning model places students at the core of the educational process, offering multiple solutions to educators, mainly when supported by learning management systems. The Geotechnics@Home initiative aims to improve blended learning and facilitate the flipped classroom approach. Students engaged in virtual classes at their own pace, which allowed in-person sessions to focus on practical applications, lab investigations, and project work. Key components of this teaching project are outlined, along with preliminary findings regarding students' academic performance. Although extending this platform to more courses and involving additional students is imperative, the preliminary results are encouraging. In the first year of implementing the platform, there was an increase in the number of evaluated and approved students. Furthermore, students' performance resulted in a smaller disparity between the best and worst results.

Keywords: *Blended learning, Flipped learning, Soil mechanics, Learning management systems, Students' performance*

1 Introduction

The COVID-19 pandemic has impacted every sector of society, including education. The numerous lockdowns experienced by many countries have accelerated the integration of digital technology in education, enabling students at all levels to continue their studies (Sathish et al., 2020). However, the shift to distance learning comes with considerable challenges, such as technological infrastructures, digital literacy, and pedagogical adaptation. Students need to develop focus and self-control, while teachers face difficulties creating engaging online content (Al Lily et al., 2020). In online learning environments, instructors evolve from teachers to facilitators. They emphasise student engagement and encourage self-motivation by supplying all necessary materials at the start of the class or course. They need also be organised and provide clear instructions on navigating the available resources. This approach fosters student collaboration and helps them develop their own understanding of the course materials (Bailey and Card, 2009). The migration to online learning environments has also allowed the enhancement of different learning approaches, transitioning from teacher to student-centred methodologies (Sathish et al., 2020), prioritising students' well-being, academic success and inclusive

educational practices while highlighting the need for continuous professional development of teachers (Sato et al., 2024). Online learning in higher education offers numerous benefits. For students, it allows them to pursue advanced degrees while staying in their current jobs, offering a range of international institutions and courses to choose from (Hosseindoost et al., 2022). Additionally, they can access a wealth of information through educational platforms (Arkorful and Abaidoo, 2015). From the institution's perspective, online learning can help alleviate operational challenges. However, notable drawbacks include the diminished interaction between students and instructors and an excessive dependence on technology (Chang, 2016).

Blended learning (b-learning) combines various teaching methods that cater to different learning methods (McSporran and King, 2005). This approach utilises a pedagogy that leverages the advantages of both in-person and online education (Osguthorpe and Graham, 2003). The focus is on achieving a balanced integration of digital access to information and direct human interaction. It's crucial for b-learning to emphasise and merge the strengths of these two different educational environments (Osguthorpe and Graham, 2003). Moreover, b-learning is most effectively utilised in the Flipped Classroom learning methodology. In this approach, students assume responsibility for their learning as they access lesson materials before attending class (Capone et al., 2017). According to these authors, teachers facilitate the proper understanding of the lesson by involving students in activities or projects where they can transfer the acquired knowledge into competencies.

This communication presents a case study at the Polytechnic University of Coimbra, Portugal, where a blended learning methodology was implemented for the Soil Mechanics course of the Civil Engineering degree. No more theoretical classes are scheduled. Students only attend theoretical-practical and laboratory courses. All the theoretical material was uploaded to the school's learning management systems (Moodle® Platform), and students attended virtual lessons at their own pace and rhythm, according to a previously presented timeline. During the practical and laboratory classes (face-to-face lessons), geotechnical challenges or problems are proposed to students so that they can apply the learning outcomes of the virtual lessons. The success of this initiative is evaluated through students' final grades. The outcomes achieved encourage the development of a collaborative e-learning geotechnical space for students enrolled in several undergraduate studies.

2 Blended learning and flipped learning enhanced by learning management systems

2.1 Literature review

Blended learning is rapidly becoming popular in higher education (Talan and Gulsecen, 2019). A fundamental component of b-learning is the diverse communication methods that connect students and teachers. When students enrol in a b-learning course, they become part of a community that encourages the exchange of questions and answers, as well as active discussions and critical debates with both peers and instructors through written communication. Garrison and Kanuka (2004) state that written communication greatly enhances synthesising skills, reflection, and accuracy. Moreover, to effectively participate in the online part of the course, students need to develop skills to navigate various activities, which boosts their self-motivation (Bevell et al., 2020). As summarised by Platonova et al. (2022), b-learning can significantly enhance academic performance and student satisfaction and decrease student retention rates.

The instructional design of a blended learning course is vital for ensuring high-quality learning. The face-to-face and online elements differ in terms of time, scope, and significance, which fluctuates from one course to another based on their specific requirements (Santos, 2018). During the design phase of a blended course, it's essential to clearly define objectives, establish assessment methods, outline content sequences, devise teaching strategies, and select the most fitting tools (Masie, 2006). This comprehensive approach is crucial for effectively addressing training needs. Masie (2006) highlights four key factors that blended course organisers should consider for success: (i) actively participating in blended learning experiences to understand the challenges students face; (ii) acquiring proficiency in all technological tools that may be used in the course; (iii) ensuring access to the appropriate technological resources; and (iv) gaining practical experience with blended learning and mastering the related technologies.

The increasing demand for technological integration in higher education is leading to new learning methods (Chi et al., 2018). In this context, traditional education can be enhanced through information and communication technologies (Fetaji et al., 2019). Methods that blend face-to-face and online lessons and activities are becoming more prevalent. Within this framework, the flipped classroom approach is starting to change the educational paradigm. The flipped classroom approach is defined as inverting the learning activities that usually occur inside and outside the classroom (Lage et al., 2000). This method strongly emphasises technology (Chi et al., 2018), as the time typically allocated for direct instruction is moved online, allowing face-to-face sessions to focus on engaging and dynamic activities. The benefits of this methodology include (Schmitt & Cequea, 2020): i) facilitating the application of higher-order thinking processes according to Bloom's taxonomy; ii) enabling students from diverse disciplines to gain various knowledge, skills, and attitudes that contribute to societal development; iii) encouraging students to take greater ownership of their learning, thereby enhancing course effectiveness; and iv) utilising in-person time for active activities and group discussions, facilitated by the instructor educator.

The defining feature of the flipped classroom is its active learning approach, where classroom time is devoted to discussing previously studied materials, such as videos and texts, instead of traditional teaching methods. This shift allows for student participation and critique (Wang, 2019). The emphasis is on learning instead of teaching, fostering greater interaction between students and instructors (Mok, 2014). As noted by this author, class time is utilised for problem-solving, addressing questions, developing critical thinking, and enhancing collaborative exercises. In this context, it's important to emphasise the definition by Bishop & Verleger (2013), who describe the flipped classroom as an educational approach comprising two elements: engaging group learning activities and individualised computer-based instruction conducted outside of it.

Although the flipped learning methodology offers several benefits, Zhang et al. (2021) note that it isn't ideal for every course. Specifically, subjects that require reasoning, conceptual understanding, and systematic approaches, like language, history, and various liberal arts, are not well-suited for flipped learning. Conversely, this approach proves advantageous for disciplines that involve abstract reasoning and logical clarity, including mathematics, physics, and chemistry. Due to their foundations in mathematics and physics, engineering courses can also be included in this last group.

From a student's perspective, flipped learning boosts engagement, motivation, and academic performance. Similar to other pedagogical methodologies with proven results in teaching geotechnical subjects, such as co-creation (Ribeiro et al., 2024), this active learning approach fosters student responsibility and promotes a deeper comprehension of learning objectives. Additionally, students learn at their own pace and learning style. Pre-class activities help alleviate anxiety, encouraging students to participate in discussions as they are already familiar with the material (Mayasari, 2024). From a teacher's viewpoint, the educator will guide on the side rather than being a sage on the stage (King, 1993). Rather than simply teaching knowledge, the teacher takes on the role of a facilitator or coach, encouraging students to construct their own understanding. Additionally, it is essential to transform learning environments to prioritise student engagement (Mazur, 2013).

While flipped learning offers several benefits, some researchers argue that its full potential is not achievable solely through learning management systems (LMS) (Rhode et al., 2017). LMS platforms are essential for broadening access to education, offering various tools for content sharing, interaction, and collaboration among students and educators. They also enable educators to monitor and report students' progress throughout the course modules. Indeed, many students face challenges accessing various learning platforms and navigating the information available. Additionally, educators may find it challenging to create effective pre- and post-class materials, such as practical activities and assessment tools, overseeing numerous course information banks and securely maintaining student databases (Pozo-Sánchez et al., 2022). The authors conclude that the flipped learning approach is advantageous and significantly improved when integrated with an LMS platform, optimising the overall learning process.

Several online LMSs are available, one of them being the Moodle® platform. Moodle is an acronym for Modular Object-Oriented Dynamic Learning Environment and presents three main advantages: i) It is an open-source platform for creating learning communities and designing online environments that support education, allowing any user to modify and adapt the environment according to their own needs; ii) It enables the publication and accessibility of resources in various formats, allowing content management, which makes it easier for teachers to make content available in different formats and to

define when and how students interact with it; iii) It includes diverse functionalities such as participation, communication and collaboration tools, course and user administration, evaluation, and activity tracking, among others. Compared to other LMS, the Moodle® platform offers several benefits: i) it operates without commercial purposes; ii) it features a straightforward and user-friendly interface for easy navigation; and iii) it demonstrates a high level of versatility in integrating new functionalities.

2.2 Learning Management System at the Polytechnic University of Coimbra

The Polytechnic University of Coimbra provides two online platforms for its students: NONIO and Moodle. NONIO serves as an academic management tool where students can enrol in courses or modules, submit requests to administrative services, obtain various documents, and check weekly timetables and evaluation dates. Additionally, it allows instructors to share course materials and upload assignments. However, NONIO is not categorised as a virtual learning environment because it lacks synchronous or asynchronous communication capabilities for interactions between students and teachers, functioning primarily as a file management system. The second platform is Moodle, a learning management system introduced earlier. Regardless of minor variations between Moodle versions, when students log into the platform, they select their pathway through their degree, the academic year, and the semester, eventually reaching the course they wish to enrol in and accessing the available information and prepared activities.

The Civil Engineering degree at the Engineering School of the Polytechnic University of Coimbra comprises thirty-six courses, with twelve each academic year and six per semester. The curriculum features four geotechnical courses: Geotechnics (fall semester of the 2nd year), Soil Mechanics (spring semester of the 2nd year), Foundations 1 (fall semester of the 3rd year), and Foundations 2 (spring semester of the 3rd year). These four courses establish the foundational geotechnical education, which is further expanded upon in the Master's in Civil Engineering. Besides these courses, students have the option to select additional geotechnical courses from the Master's in Sustainable and Smart Cities, the Sustainable Cities Management Degree, as well as the Civil Protection Technical Course and the Civil Construction and Public Works Technical Courses, among other education offer. While the syllabus length may vary based on the specific degree characteristics, it addresses topics that are, to varying extents, included in the syllabuses of the four fundamental courses. For teachers, the structure of Moodle leads to the dissemination of information across various courses, necessitating the management of multiple Moodle pages that occasionally feature similar content.

3 Geotechnics@Home project

Geotechnics@Home project is an ongoing project based on online activities developed during the COVID-19 pandemic. In Portugal, two lockdowns were imposed on the population to prevent and control the spread of disease and safeguard the national health system. Both lockdowns affected the spring semester, and most classes had to be substituted by online synchronous and asynchronous moments. As a result, several online Soil Mechanics lectures were prepared and proposed to students. These lectures have been revised and adapted for integration into a blended learning model, utilising flipped learning methodology boosted by Moodle features.

Geotechnics@Home is designed to enhance, not replace, the official course page on Moodle platform where teachers provide updates and all the relevant information on ongoing geotechnical courses. This learning tool aims to support all geotechnical studies by offering essential knowledge in the field. It functions similarly to a Soil Mechanics and Geotechnical Engineering textbook, leveraging the advantages of a digital environment. Regardless of the lecturers' teaching method, students can always use the platform to either engage with required module lectures or just complement the topics discussed during in-person classes. The first option positions this project as a b-learning platform, facilitating a flipped learning approach. Conversely, if the teacher opts not to utilise the platform, students can independently engage with it as an e-learning tool, selecting the material they wish to explore further. Whatever the reason for using the platform, feedback to the student is always guaranteed either by the lecturer responsible for the course or by any other geotechnical lecturer with access to the platform.

The platform also monitors student activity for various reasons based on usage stage. Currently, tracking occurs through task completion criteria and badges. These criteria motivate students to participate in all activities, which is crucial during the initial phases of their experience. For instance, they help develop

habits in using asynchronous communication methods like forums and chats, which are vital in blended or online learning environments. However, many students often hesitate to utilise these tools. To encourage participation, completion criteria require students to engage with a certain number of posts or replies. Other conditions may prevent students from progressing on the platform until specific tasks or grades are achieved, ensuring a structured learning path while allowing students the freedom to explore their interests and make choices. Badges work as rewards for achievements and intend to keep students motivated.

As part of a flipped learning approach, students are invited to follow the pre-established virtual lectures. These lectures replace the traditional teaching of theoretical content at the beginning of classes or whenever new concepts are introduced. Scheduling topics in advance allows students to manage their theoretical study time independently and at home (or elsewhere), ensuring they have the necessary knowledge/skills when practical application is required. This approach allows face-to-face class time to focus entirely on solving exercises, working on projects, conducting lab investigations, and engaging in other activities. It should be noted that this methodology does not involve teachers utilising synchronous moments for theoretical explanations. Instead, teachers promote sharing knowledge gained during self-study, facilitating student interactions and offering guidance to enhance understanding. The process should prioritise asynchronous communication to support the active construction of student knowledge.

3.1 Getting started with the platform

In a blended learning model, getting started with the platform is essential for engaging all students enrolled in the course. The proposed activities should enable students to familiarise themselves with the platform, connect with participants, and level all the students in information and communication technology skills necessary for effective platform usage. The more students immerse themselves in the platform, the higher their chances of retaining information and maintaining motivation. Several activities can be proposed: newsletters, forums for quick presentations, a global glossary that will be continually updated with students' information, and various submission tasks (Figure 1).

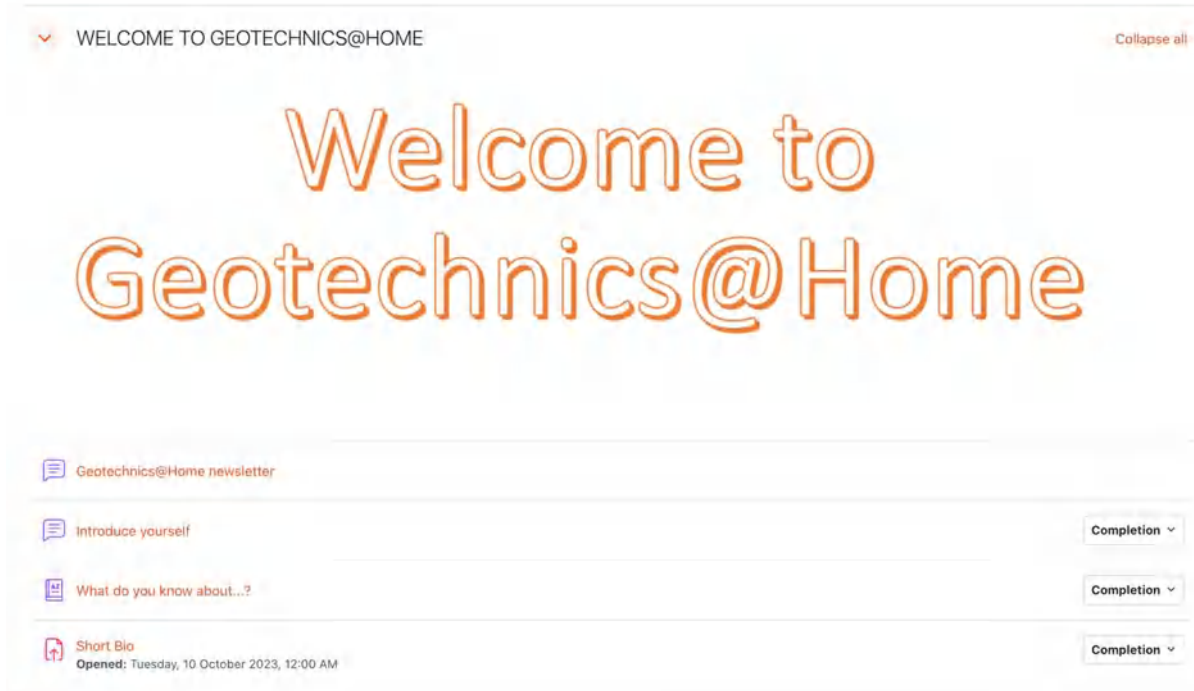


Figure 1. Getting started with Geotechnics@Home: homepage

At this point, including the course's general information is essential. Students must be able to access all pertinent details, such as the course description, intended audience, prerequisites in skills or knowledge, syllabus, learning objectives, teaching methods, resource and technology needs, communication tools, and assessment procedures. The schedule and timetable must also be communicated to the students

at the beginning of the course, especially when using the platform is an integral part of the course's teaching methodology. Students will embark on an autonomous study journey and must be guided throughout. This information should be compiled into a single, interactive document, and its completion must be mandatory to ensure that all students understand what is expected of them, when, and how. For instance, utilising the resource book of the learning management platform is advisable. To maintain student motivation, engaging activities should be created to boost awareness and curiosity about upcoming topics. As Geotechnics@Home welcome session, it was chosen the lecture Enigma of the Leaning Tower of Pisa, given by Professor Burland in 1998 (Burland, 1998) (Figure 2). These activities should be optional but can lead to badges students earn throughout their blended learning journey.

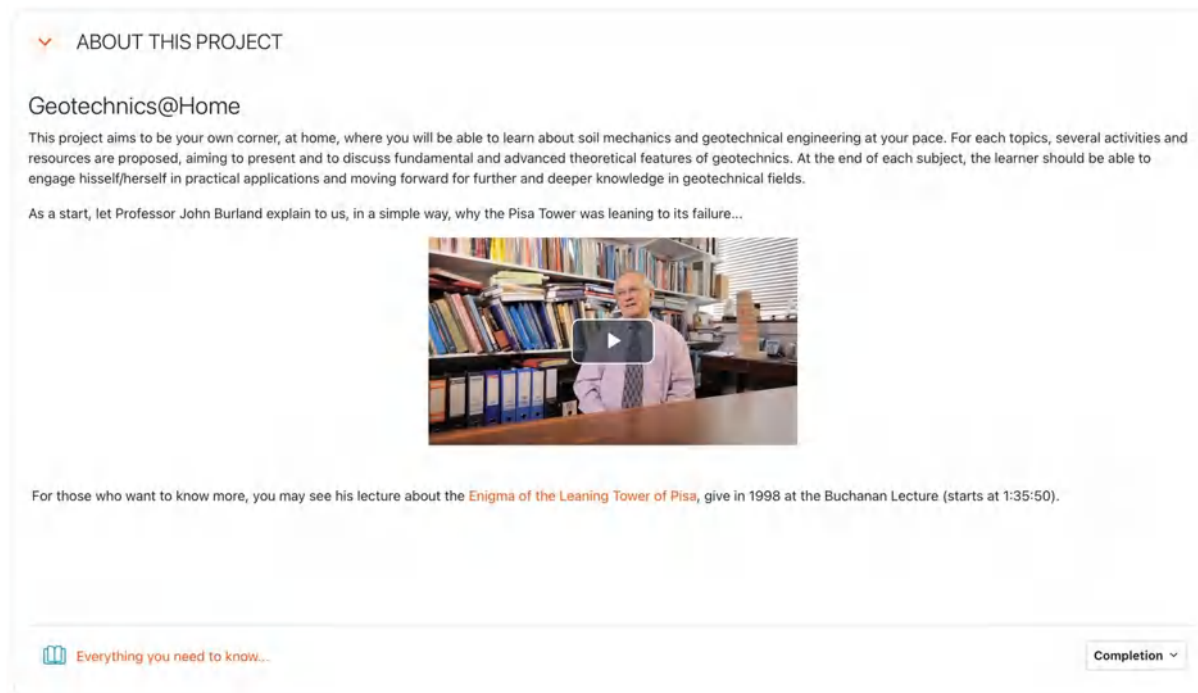


Figure 2. Getting started with Geotechnics@Home: about the project

3.2 Students' Corner

A key component of this project is the ongoing contact between teachers and students, and this unique space has been created to promote the sharing of ideas, doubts, and other useful information. Student's Corner comprises three features:

1. Attendance and summary: This Moodle activity is most effective when the platform is utilised in a flipped learning model. Consolidating all information in one location aids students' progress. Students remain informed about what has been accomplished and what is planned for the face-to-face class.
2. Cybercafe: Geotechnics@Home hosts its official chat platform where students and teachers can discuss any topic, whether related to geotechnical engineering or not. This casual environment fosters user interaction, enhancing their sense of belonging to the platform community.
3. GeoHelp: It is the project's global forum. Students should direct any questions or concerns regarding the platform, its integration with courses, or active learning methodologies to this forum. It is a collaborative space where both teachers and students can respond to posts. For personal matters, students can always contact teachers via private messaging, meetings during office hours, or any other communication method.

3.3 Main lectures

Geotechnics@Home is built on top of the foundational lessons. Every class follows a similar format (see Figure 3): i) a lecture on the topic, ii) a dedicated forum for questions, and iii) a self-evaluation test. As illustrated in Figure 4, the lectures follow a standard framework. The welcome page offers a concise

overview of the topic and outlines the four main sections of the lecture (Revisions, Lecture, Written documents, Self-assessment). To complete a lesson, students must engage with all activities and achieve a passing grade in the self-assessment section. This requirement is crucial primarily when the platform supports flipped learning strategies. In a more open usage, students can directly access the lecture content.

There is no hierarchy among lessons on the platform. Introducing such a limitation would restrict users from accessing their preferred lessons. Access conditions for lesson topics arise only when they are divided into various issues, either due to their complexity or the number of subjects addressed. This conditional access ensures coherence in content presentation. The revision chapter includes questions to confirm that students have the requisite knowledge to fully understand the material presented. If students cannot answer the revision questions, they are encouraged to revisit a specific lesson.

All lectures have been uploaded to YouTube, but the channel is private. Access to the videos is restricted to the link in the Lecture chapter of the main lesson. In an earlier version of the Geotechnics@Home project, the video lectures were directly embedded in the Moodle platform. While this approach offered better data and content protection, it overloaded the institutional servers hosting Moodle. The video durations range from under 7 to 30 minutes, averaging 20 minutes. The streaming platform serves solely to visualise the lesson. Feedback or other interactions are not provided. Any issues, questions, or concerns must be reported in the dedicated lesson forum.

The final two chapters of the lesson are Written Documents and Self-assessment. The Written Documents chapter offers links to suggested and supplementary reading materials. While the platform includes essential bibliographic details for various courses, users can always access a direct link to the main course page. The Self-assessment section features questions designed for students to evaluate themselves. It's important to highlight that, in contrast to the Revision chapter, which requires students to answer all questions correctly to proceed, this Self-assessment allows students to navigate through different questions and receive a final grade. If the grade is positive, the lesson is marked as complete. Conversely, if the grade is negative, students are encouraged to review the lesson before attempting the self-assessment again.

The screenshot displays the Geotechnics@Home main lessons interface. It features two lesson cards. The first card, titled 'HYDRAULICS IN GEOTECHNICS AND SEEPAGE', has a 'MAIN LESSON' section with a video icon and a 'DOUBTS & MORE' section with a forum icon. Below the forum icon is a message: 'Not available unless: The activity introduce yourself is incomplete ...'. The second card, titled 'STRESS IN THE GROUND', also has a 'MAIN LESSON' section with a video icon and a 'DOUBTS & MORE' section with a forum icon. Both cards have a 'Self-evaluation test' at the bottom.

Figure 3. Geotechnics@Home main lessons: general structure

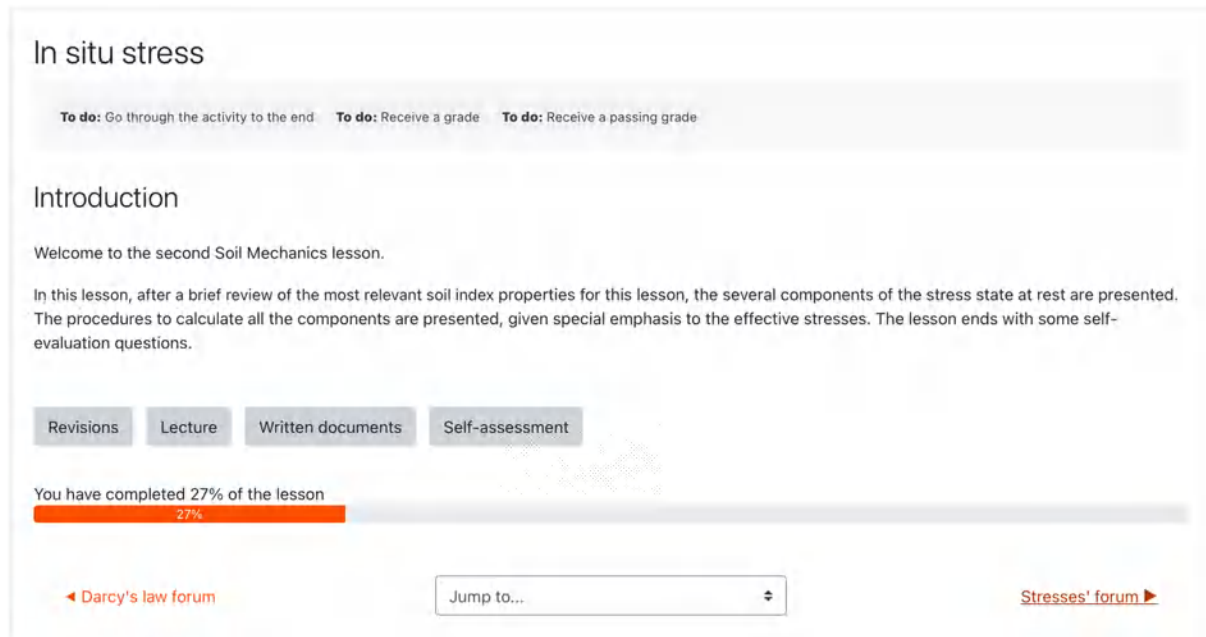


Figure 4. Geotechnics@Home main lessons: example of the In situ stress lesson

In the lessons, any questions or doubts should be posted in the doubt forum. This forum encourages collaboration, allowing both students and teachers to respond to inquiries. Teachers also play a supervisory role, ensuring that student responses are accurate and, if needed, providing supplementary information or explanations. Students are finally given the opportunity to undertake self-evaluation tests. These tests are automatically generated from a pool of questions from a database. This question database has been continuously updated since the first COVID-19 lockdown in 2020 and contains dozens of questions. It features both open-ended (long or short) and closed questions. Nearly 20 closed question types are available, including single and multiple-choice, true/false, numeric, matching, sorting, drag-and-drop to text or image, fill-in-the-blanks, and dropdown boxes, among others. Each self-evaluation test presents 20 randomly chosen questions in a shuffled order, with the answer options also displayed randomly. The time for answering is restricted; the platform automatically concludes the attempt and saves the students' responses, allowing each student only two attempts at the self-evaluation test. The initial attempt serves well as a self-evaluation activity. Afterwards, students will receive feedback and a grade from the teacher. It's important to mention that the platform does not offer automatic feedback due to the open-ended questions, which require human review. Following the feedback, students have a chance for a second attempt, which may consist of either another self-evaluation or a final grade for the lesson topic, depending on how the platform is used pedagogically. In an e-learning context, where students navigate the platform independently, the grade serves as an informational tool for the student. When Geotechnics@Home is used to enhance flipped learning, the final grade's role as an assessment will vary according to the course syllabus and learning agreement, which must be communicated to and accepted by the student in a distance learning methodology.

4 Results: Students' performance

Geotechnics@Home debuted for students enrolled in the Soil Mechanics course during the 2023/2024 academic year. This marked the first implementation of the flipped learning active learning approach in the course. Although it is premature to make definitive conclusions, analysing the students' performance reveals promising data that advocates for the continued use of this methodology and further development of the platform and its implementation in other courses. Table 1 summarises academic results since the current lecturer assumed responsibility for the course. Due to differing evaluation conditions, the academic year 2019/2020 has been omitted from this summary. During the COVID-19 lockdown, assessments for students occurred remotely rather than in person, as done in previous years. Aside from the evaluation and approval percentages for students in the 2020/2021 academic year, the overall results for the 2023/2024 academic year, the implementation year of the platform, are better

across all domains. Higher, lower, and average grades are either improved or comparable when only the approved students are considered. Additionally, when comparing the second highest and lowest grades, student performance was as good as in prior years, or even better, leading to a smaller disparity between the best and worst results.

Table 1. Final grade evolution in the last 6 years

	2023/2024	2022/2023	2021/2022	2020/2021	2018/2019	2017/2018
Students evaluated	76%	69%	60%	81%	47%	85%
Students approved	92%	89%	78%	100%	100%	82%
Higher grade	17	15	14	15	16	17
Lower grade*	11	10	10	10	11	11
Average grade*	14.7	13.4	11.7	11.5	13.6	14.7
2 nd higher grade*	16	15	14	13	14	17
2 nd lower grade*	13	11	10	10	13	11
Amplitude	3	4	4	3	1	6

* The values presented were based solely on the sample of approved students.

6 Conclusions

Geotechnics@Home is more than a course Moodle page. It aims to be a learning platform for all the geotechnics-related courses taught in the Institute of Engineering of the Polytechnic University of Coimbra. This project has been implemented and developed to enhance electronic and blended learning, supporting active learning methodologies like flipped learning. The first impressions clearly show that this initiative helps students to achieve better academic results and, of course, to develop the necessary skills for their profession. To confirm and improve the encouraging results of this initial implementation, the platform should be used in additional courses and engage more students.

The project will soon include Experience points (XP) and different user levels, leveraging Moodle's gamification elements, in addition to continuously updating courses and lectures to improve the platform's adaptability and applicability. Gamification's advantages in remote learning settings are well acknowledged and ought to be further maximised. In relation to the lectures, new platforms like VideoAnt and Hypothes.is should be used to improve video interactivity and make reading tasks easier.

References

- Al Lily, A. E., Ismail, A. F., Abunasser, F.M., Alhajhoj Alqahtani, R.H. (2020). Distance Education as a Response to Pandemics: Coronavirus and Arab Culture. *Technology in Society*, 63, 101317.
- Arkorful V, Abaidoo N. (2015). The role of e-learning, advantages and disadvantages of its adoption in higher education. *International Journal of Instructional Technology and Distance Learning*, 12(1), pp. 29-42.
- Baily, C. J., Card, K. A. (2009). Effective pedagogical practices for online teaching: perception of experienced instructors. *Internet and Higher Education*, 12, pp. 152-155.
- Bervell, B., Nyagorme, P., Arkorful, V. (2020). LMS-enable blended learning use intentions among distance education tutors: examining the mediation role of attitude based on technology-related stimulus-response theoretical framework. *Contemporary Educational Technology*, 12(2), ep273.
- Bishop, L. L., Verleger, M. A. (2013). The flipped classroom: a survey of the research. *Proceedings of the 120th Annual Conference & Exposition*, 6219. Atlanta, USA.
- Burland, J. B. (1998). The enigma of the leaning Tower of Pisa. The Sixth Spencer J. Buchanan Lecture. Texas A&M University.
- Capone, R., De Caterina, P., Mazza, G. (2017). Blended learning, flipped classroom and virtual environment: challenges and opportunities for the 21st century students. *Proceedings of EDULEARN17 Conference*, pp. 10478-10482, Barcelona, Spain.

- Chang, V. (2016). Review and discussion: e-learning for academia and industry. *International Journal of Information Management*, 36(3), pp. 476-485.
- Chi, Y. L., Chen, T. Y., Hung, C. L. (2018). Learning adaptivity in support of flipped learning: an ontological problem-solving approach. *Expert Systems*, 35(3), e12246.
- Fetaji, M., Fetaji, B., Ebibi, M. (2019). Analyses of possibilities of flipped classroom in teaching computer science courses. *Proceedings of the 42nd International Convention on Information and Communication Technology, Electronics and Microelectronics*, pp. 747-752, Opatija, Croatia.
- Garrison, D. R., Kanuka, H. (2004). Blended learning: uncovering its transformative potential in higher education. *Internet and Higher Education*, 7, pp. 95-105.
- Hosseindoost, S., Khan, Z. H., Majedi, H. (2022). A shift from traditional learning to e-learning: advantages and disadvantages. *Archives of Neuroscience*, 9(2), e128031.
- King, A. (1993). From sage on the stage to guide on the side. *College Teaching*, 41(1), pp. 30-35.
- Lage, M. J., Platt, G. J., Treglia, M. (2000). Inverting the classroom: A gateway to creating an inclusive learning environment. *Journal of Economic Education*, 31(1), pp. 30-43.
- Masie, E. (2006). The blended learning imperative. In: Bonk, C. J., Graham, C. R. (eds). *The handbook of blended learning: global perspectives, local designs*. Pfeiffer, San Francisco, USA, pp. 22-26.
- Mayasari, A. R. (2024). The impact of the flipped classroom model on student engagement and academic achievement: a systematic review of the literature. *International Journal of Teaching and Learning*, 2(11), pp. 3136-3146.
- Mazur, E. (2013). The flipped classroom will redefine the role of educators. *The EvoLLLution*. Available online at: https://evollution.com/revenue-streams/distance_online_learning/audio-flipped-classroom-redefine-role-educators-10-years
- McSporran, M., King, C. (2005). Blended is better: choosing educational delivery methods. *Proceedings of EdMedia: World Conference on Educational Media and Technology*, Kommers, P., Richards, G. (Eds.), pp. 4932-4939, Chesapeake, Montreal, Canada.
- Mok, H. N. (2014). Teaching tip: the flipped classroom. *Journal of Information Systems Education*, 25(1), pp. 7-11
- Osguthorpe, R. T., Graham, C. R. (2003). Blended learning environments: definitions and directions. *Quarterly review of distance education*, 4(3), pp. 227-33.
- Platonova, R. I., Orekhovskaya, N. A., Dautova, S. B., Martynenko, E. V., Kryukova, N. I., Demir, S. (2022). Blended learning in higher education: diversifying models and practical recommendations for researchers. *Frontiers in Education* 7, 957199
- Pozo-Sánchez, S., Segura-Robles, A., Moreno-Guerrero, A. J. y López-Belmonte, J. (2022). Benefits of using the learning management system based on flipped learning methodology. *Revista Electrónica de Investigación Educativa*, 24, e24.
- Rhode, J., Richter, S., Gowen, P., Miller, T., & Wills, C. (2017). Understanding faculty use of the learning management system. *Online Learning*, 21(3), pp. 68-86.
- Ribeiro, V. C., Proença, S. I. A., Araújo Santos, L. M., Gonçalves, J. A. P. (2024). Co-creation as a driver of geo-environmental learning approach to adapt cities to climate change. *Soils and Rocks* 47(2), e2024004823
- Santos, M. I. L. F. (2018). The integration of e-learning platforms in an educational context: A model for continuous teacher education. University of Coimbra, Faculty of Psychology and Educational Sciences, Coimbra, Portugal (in Portuguese)
- Sathish, M. T., Sornaganesh, V., Sudha, G., Chellama, A. V. (2020). A study on shift of traditional classroom methods to online teaching methods in higher education scenario during lockdown. *International Journal of Multidisciplinary Research and Development*, 7(7), pp. 96-100.

Sato, S. N., Moreno, E. C., Rubio-Zarapuz, A., Dalamitros A. A., Yañez-Sepulveda, R., Tonero-Aguilera, J. F., Clemente-Suárez, V. J. (2024). Navigating the new normal: adapting online and distance learning in the post-pandemic era. *Education Sciences*, 14, 19.

Schmitt, V. G. H., Cequea, M. M. (2020). Flipped classroom: a paradigm shift in higher education. *Interciencia*, 45(11), pp. 501-507. (in Portuguese).

Talan, T., Gulsecen, S. (2019). The effect of a flipped classroom on students' achievements, academic engagement and satisfaction levels. *Turkish Online Journal of Distance Education*, 20(4), pp. 31-60.

Wang, F. H. (2019). On the relationships between behaviors and achievement in technology-mediated flipped classrooms: a two-phase online behavioral PLS-SEM model. *Computers and Education*, 142, 103653.

Zhang, Q., Cheung, E. S. T., Cheung, C. S. T. (2021). The impact of flipped classroom on college students' academic performance: A meta-analysis based on 20 experimental studies. *Science Insights Education Frontiers*, 8(2), pp. 1059-1080.

Authors' bios

Luis Araújo Santos, Polytechnic University of Coimbra, Coimbra Institute of Engineering (Portugal)

Since 2004, Luis Araújo Santos has been an adjunct professor at the Coimbra Institute of Engineering, part of the Polytechnic University of Coimbra. He teaches geotechnical courses in various undergraduate and graduate programs. With a strong academic background in geotechnical engineering and environmental studies, he has focused on researching granular soils and geomaterials through the use of unconventional testing equipment. His research and teaching have recently focused on waste management and industrial and mining waste valorisation in transportation and geotechnical engineering applications. His passion for teaching and pedagogy has driven him to participate in numerous training courses in higher education pedagogy, focusing specifically on active learning methodologies and co-creation project facilitation. He recently completed a postgraduate course in distance learning and earned several micro-credentials in online education. His combined scientific and teaching skills have enabled him to successfully implement less conventional learning approaches in soil mechanics and environmental classes.

Vera Cristina Ribeiro, Higher Institute of Educational Sciences, CI ISCE – Research Centre (Portugal)

Coordinating Professor at ISCE Douro and Adjunct Guest Professor at the Coimbra School of Education of the Polytechnic Institute of Coimbra. Lecturer on the degrees in Social Communication, Organizational Communication and Multimedia Communication and Design. Researcher at the Social Sciences and Humanities Research Centre (NICSH), part of the Human Potential Development Centre of the Institute of Applied Research (i2a) of the Polytechnic of Coimbra, whose aim is to promote fundamental and applied research in the field of Social Sciences and Humanities.

Sara Proença, Coimbra Agriculture School, CERNAS (Portugal)

Sara Proença is adjunct professor at the Polytechnic University of Coimbra (PUC), Portugal, since 2003. Teaching experience in entrepreneurship, business management, and economics. Currently, she is the Director of the INOPOL Entrepreneurship Academy of PUC. She was Pro-President of PUC for innovation and entrepreneurship (2019-21). Her academic background is in Economics (PhD) and Applied Economics (M.Sc.). Her thesis, "Impact Assessment of Energy and Climate Policies: A Hybrid Bottom-up General Equilibrium Model (HyBGEM) for Portugal, " was distinguished with the António Simões Lopes prize - best PhD thesis in Economics and Business Sciences. She also has advanced training in Entrepreneurship. Integrated member of the Research Center for Natural Resources, Environment and Society. Research experience in applied economics with publications in peer-reviewed

journals. Participation in national and international R&D+I projects and referee of numerous scientific papers. Participation in several national and international seminars and conferences.

Use of virtual reality for teaching geotechnics – application to the study of an abandoned underground mine

O. Deck

Université de Lorraine, GeoRessources, Nancy, France
olivier.deck@mines-nancy.univ-lorraine.fr

ABSTRACT: This paper describes an innovative teaching activity based on the use of a 3D virtual model of a real abandoned underground mine exploited using the room-and-pillar method and located at a depth of several dozen meters. The model covers an area of about 1 hectare, composed of approximately 25 rooms and about 15 pillars made of in-situ rock or reconstructed (dry stones). The model consists of 80 measurement stations (3D scans and 360° photos). The educational activity is conducted in three stages. The first stage consists of visiting the site to learn how to use the model, get a first impression of the environment, and discover the mining techniques used. The second stage involves a guided analysis, where points of interest are indicated for students to analyze the fracturing of the pillars and roof (whether natural or mechanical in origin). The third stage involves a stability analysis, combining previous observations with some simple calculations, such as using the tributary area model to estimate the stress state of the pillars or the calculation of the roof reinforcement with bolts. A feedback session is also offered to highlight the strengths and weaknesses of the approach.

Keywords: Virtual model, Mine, Practical work

1 Introduction

The techniques associated with virtual reality have reached a level of maturity that allows fairly easy access to 3D models that can be used for training. Depending on the teaching situation (small group, large group, face-to-face or at home), we may favor visualization using virtual reality headsets or more simply on computer screens. 3D models can be composed of geometric objects simulating reality (BIM model for example), geometric objects resulting from a real capture of reality (3D scan or photogrammetry for example) or a combination of the two.

Several tools dedicated to learning geotechnics in the broad sense have been published. García-Vela et al. (2020), for example, present different tools allowing them to replace field trips that are difficult to organize (travel costs, student safety, availability of companies) with immersive experiences where students collect information from tunnels, mines and rock slopes in order to exploit them. Gürsoy & Buyuksagis (2024) present a virtual reality tool in underground mining education to enhance machinery comprehension. Janiszewski et al. (2020) present two virtual reality models dedicated to teaching to identify rocks and minerals or to carry out structural surveys and rock mass characterization. Afsharipour & Maghoul (2023) use virtual and augmented reality to teach soil mechanics concepts. The feedback provided generally conclude an added value for students and teachers. The feedback provided generally concludes that there is added value for students and teachers.

2 Presentation of the activity

The proposed activity involves studying the stability of an abandoned underground iron ore mine using a 3D model utilizing 360° photographs and laser scan measurements taken within the mine. The use of a virtual model appears to be an attractive solution for:

- avoiding the organizational constraints associated with a real-life visit (cost, travel time, student safety);
- reproducing a realistic situation for an engineer conducting a geotechnical assessment: collecting data, identifying geotechnical issues, and proposing and sizing solutions.

The mine consists of a fairly old operation (around 1850), made up of rooms, pillars and embankments. It corresponds to an intermediate period of exploitation between the first works whose geometry seems completely anarchic and the industrial period where exploitation follows a very geometric pattern. The use of explosive shots made it possible to achieve a certain regularity of work.

The educational activity takes the form of practical work carried out by groups of 4 to 5 M2 level students in an engineering course in Geosciences and Civil Engineering (Ecole Nationale Supérieure des Mines de Nancy, France). Prerequisites are academic knowledge in engineering geology and rock mechanics, but no complex calculations are expected. The educational sequence lasts 3 hours at the end of which the students have an additional time (about 2 weeks) to write a report in the form of an expert report according to a plan proposed by the teacher.

The available documents for the activity are the following:

- Site plans allowing the location of the sector studied and the approximate geometry of the works (Figure 1). The area studied has a surface of approximately 0.5 ha.
- The 3D model (Figure 2) composed of 80 360° photographs and millions of points (Laser scan).
- The results of a geological drilling carried out near the mine (drill C104).
- A document on reinforcement by bolting accompanied by pull-out tests supposedly carried out on the roof of the galleries.
- Two detailed base maps representing the studied area.
- Extracts from a work concerning “the history of the mines of Moyeuvre” (Spanier, 1914) in which information can be found concerning the evolution of mining techniques from 1832 to 1913, a description of the extracted deposit and information on the faults and joints existing nearby.

The plan of the article follows that of the practical work in which the following work is requested (Table 1). The time schedule indicated is that proposed by the teacher for the supervised activity. Students work alone (groups of 5) for 3 hours with regular discussions with the teacher. Personal work time at the end of the session is estimated at around 2 hours per student to achieve the final report. The actual time of personal work has not been asked.

Table 1. Proposed schedule for the students during the 3h sequence

Part 1 – 1 hour	Discovery of the model and familiarization with the documents Read the statement in full (10 minutes) Watch a 3D model presentation video (10 minutes) Consult the accompanying documents (20 minutes) Visit the mine (20 minutes) – identify pillars, embankments, collapsed areas, view associated annotations and photos
Part 2 – 1 hour	Analysis of the site, disorders and discontinuities Carry out a simplified lithostratigraphic profile Create a diagram of the roof discontinuities Create a figure to distinguish the embankments from the pillars Identify the extracting method Identify and comment on the different observable disorders
Part 3 – 1 hour	Geomechanical analysis Calculate the extraction ratio and the associated safety coefficients. Propose a roof bolting reinforcement (nature of bolts, length and number of bolts/m ²)

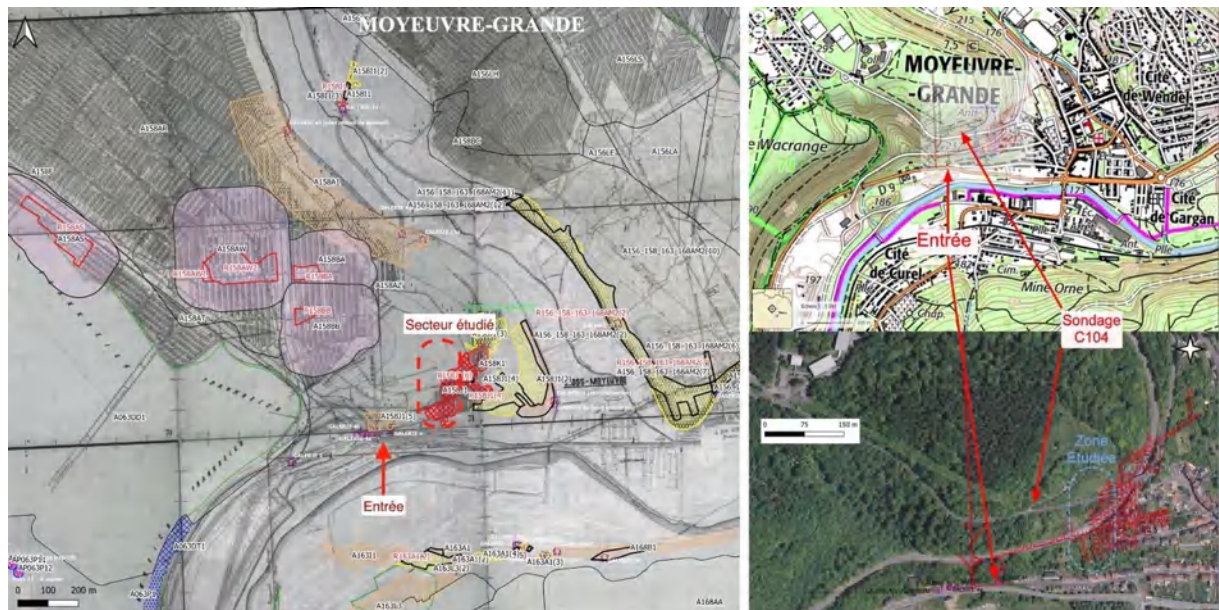


Figure 1. Location of the mining sector studied. Left) situation in relation to all the mining works located in the sector, Right-Up) Topographic map of the sector, Right-down) Aerial view of the sector.

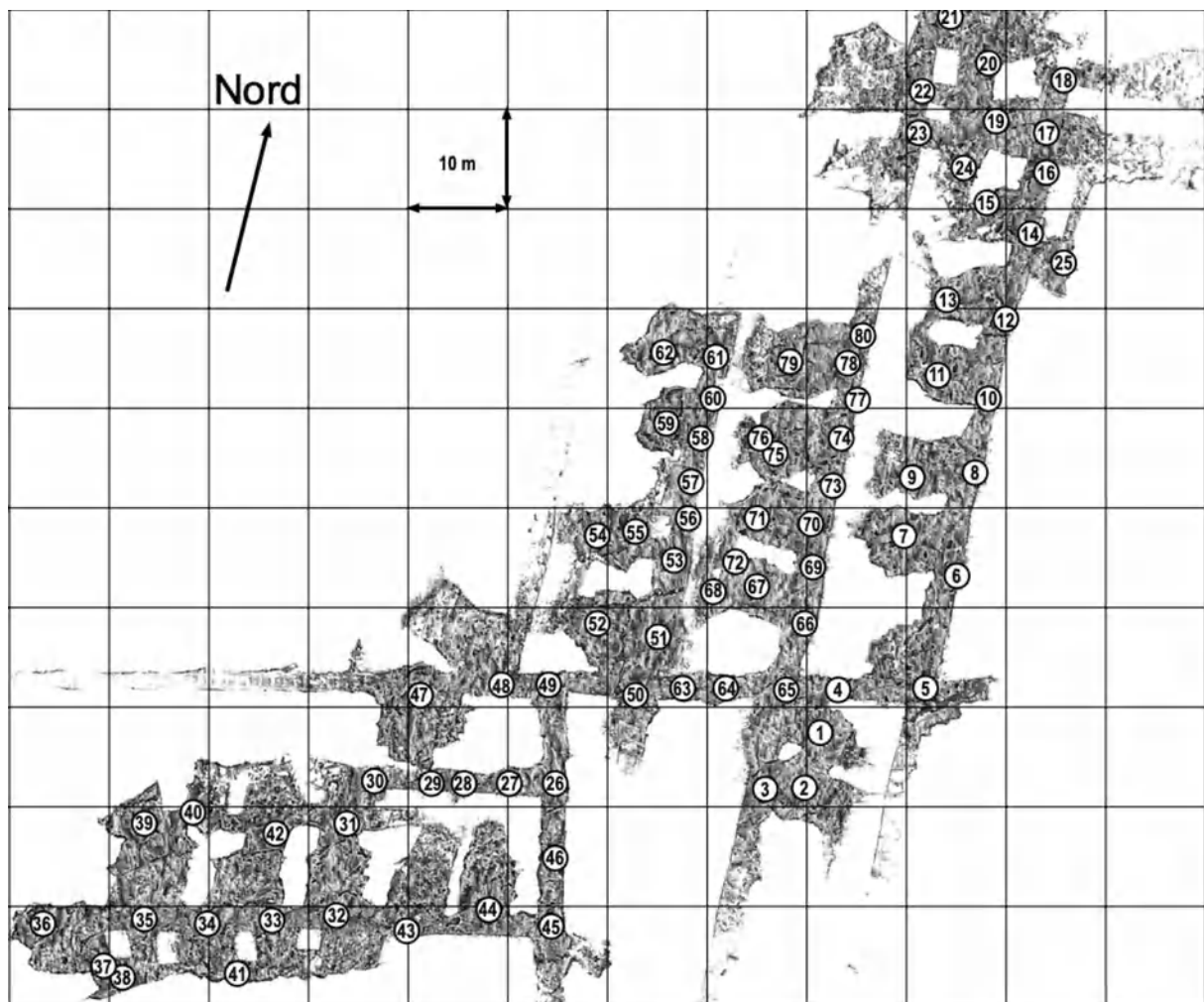


Figure 2. Map of the model produced from the 3D scan and location of the 80 stations where 360° photos are also accessible

3 Part 1 - Discovery of the model and familiarization with the documents

The model is accessible on the Web from any computer (Cintoo technology). The user has a view of the mine in the form of eighty 360° image (Figure 3) with a location on the map. Different visualization modes are possible: photographic image or colored point cloud. When the coloring is that of the photograph, the two renderings are almost identical. When the coloring is based on the reflectance of the walls, this provides access to a black and white image which has the advantage of making the underexposed areas of the photography visible (Figure 4). The 3D scan also makes it possible to carry out measurements in the mine and to visualize altitude iso values (Figure 5).

The model is also supplemented with annotations allowing access to comments and downloading higher definition photos in order to more clearly observe the discontinuities (Figure 7) and disorders (Figure 6) visible in the mine.

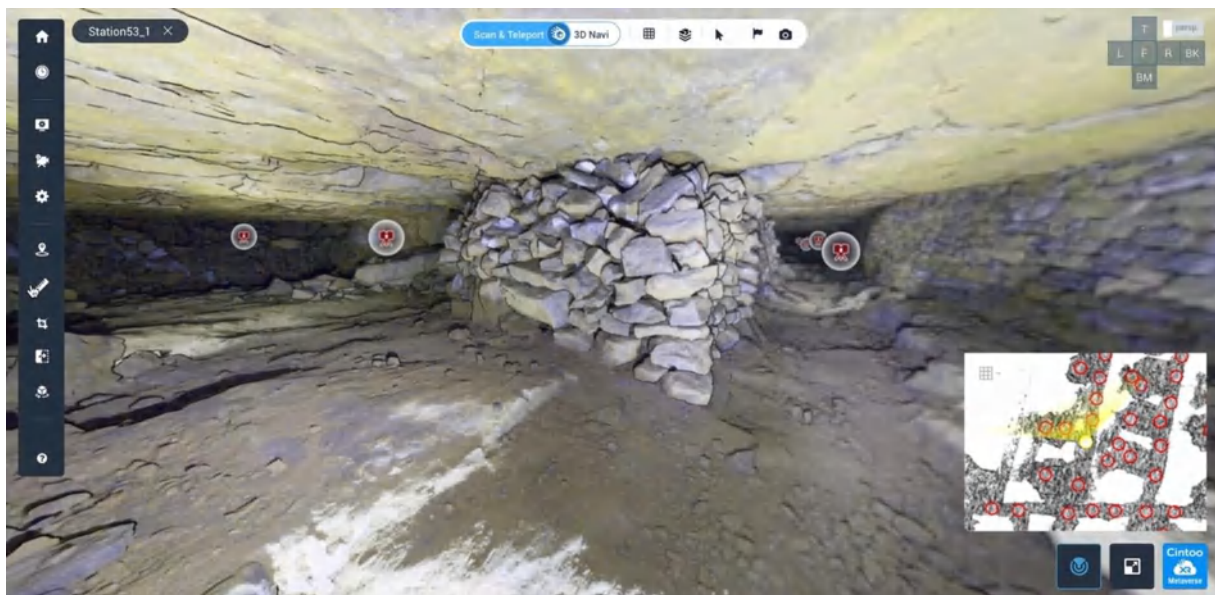


Figure 3. Example visual of 360° photos. The red icons on the image or on the map correspond to other places for viewing 360° photos. On the plan, a yellow angular sector allows you to know the orientation and angle of view.

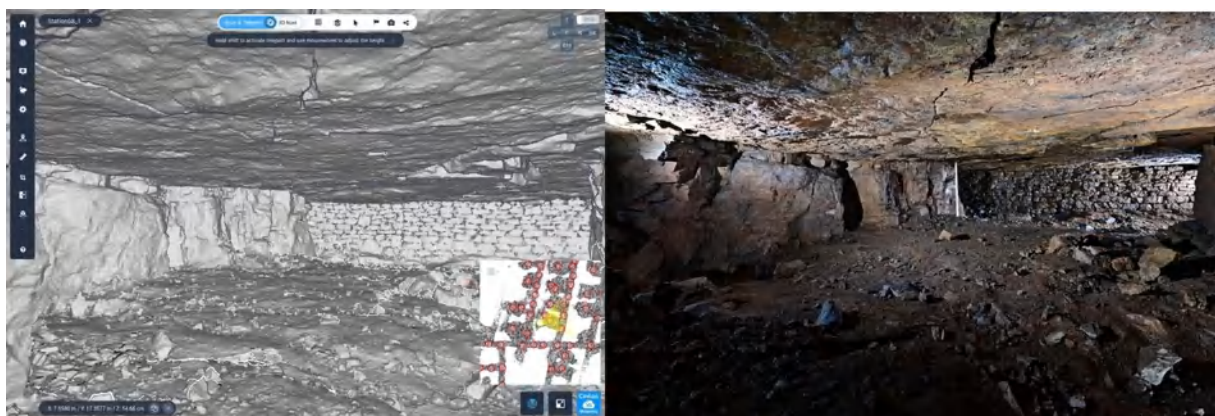


Figure 4. Example of a colored view (B/W) using wall reflectance, compared to a photograph from a similar viewing angle. The very visible discontinuity in the roof is also visible in the 360° photo. This same discontinuity is perfectly visible on the top view of the model.

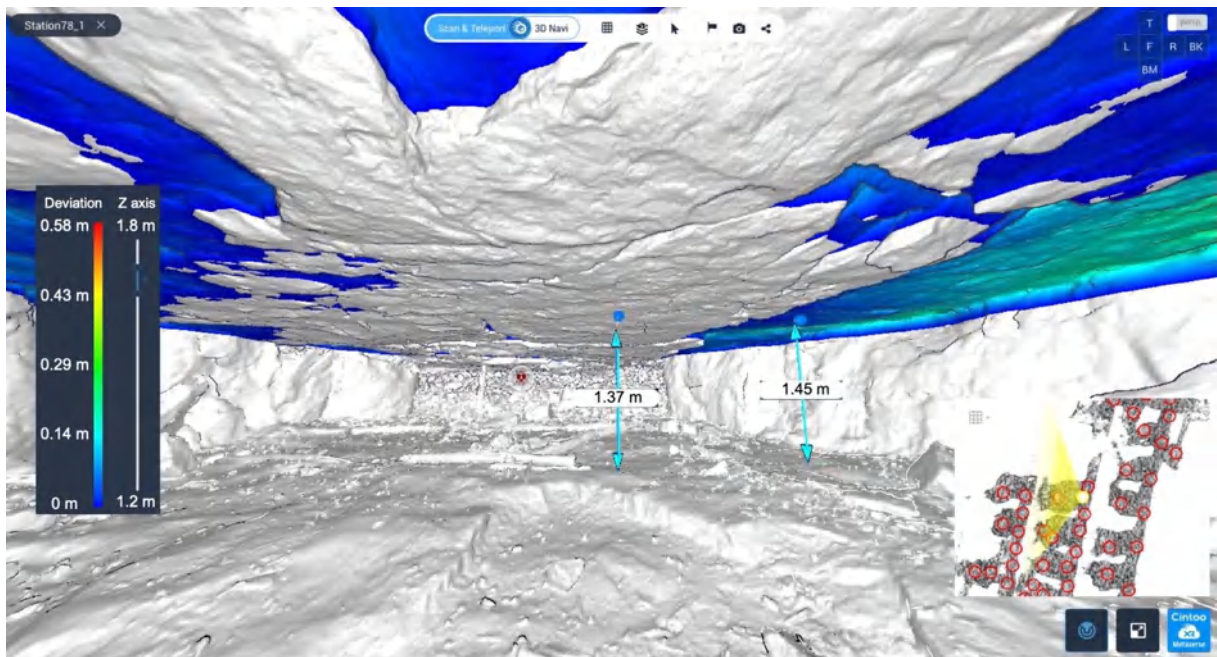


Figure 5. Example of iso-values of the altitude in a room. We observe that the roof in the center of the chamber is at a lower altitude than near the pillars, which suggests the existence of a sagging of the roof.



Figure 6. Example of photos accessible from the model and allowing visualization of disorders such as cracks in pillars (left) or in embankments (center) and roof instabilities (right)

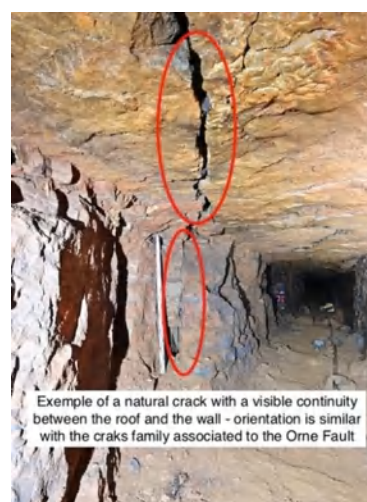


Figure 7. Example of photos accessible from the model and allowing a natural discontinuity to be visualized

4 Part 2 - Analysis of the site, disorders and discontinuities

The use of laser scanning provides access to a plan of the exploitation in black and white, where the solid areas are white (no measurements) and the exploited areas are filled with a texture that appears random at first glance. A more detailed observation allows to see in this texture some alignments that reveal the discontinuities located in the roof. The signature of these discontinuities is explained by the mask effect created by these discontinuities (Figure 8). Students are encouraged to observe this phenomenon and ensure through observations in the digital model that these alignments really correspond to discontinuities.

It is then possible to make a survey of these discontinuities from which the existence of 2 main families emerges, one oriented North, the other oriented N070 (Figure 9).

This observation can then be cross-referenced with archival documents (Figure 10) indicating the presence of two faults nearby, associated with a set of parallel discontinuities which strongly influenced the direction of the extraction works. Other discontinuities do not seem to belong to these two families (in green in Figure 9) and can be interpreted as discontinuities of mechanical origin associated with redistribution of stresses and ruptures of the roof of the galleries and chambers. Associated with the observation of locally collapsed areas, these different observations allow students to question the evolution of the mine and the risks of local instability (falling roof slabs).

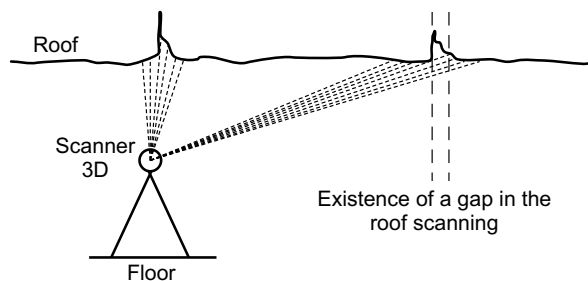


Figure 8: Explanation of the presence of voids in the 3D scan when discontinuities are not located directly above the scanner

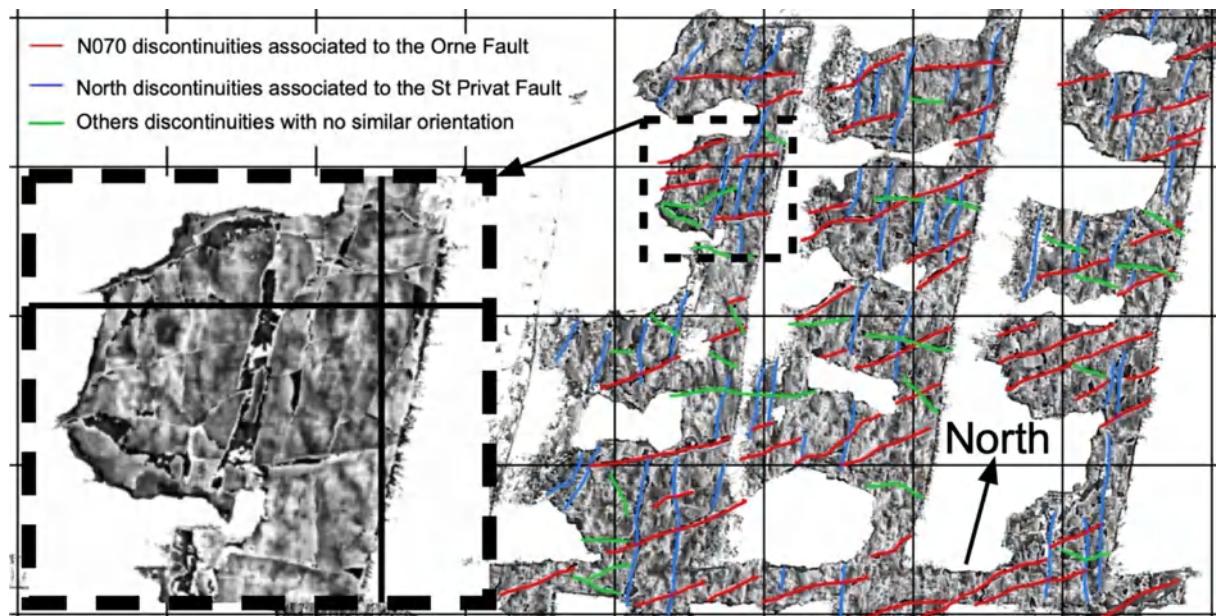


Figure 9. Visualization of the plan view obtained with 3D scan measurements and identification of discontinuities in the roof, where 3 families of discontinuity can be observed

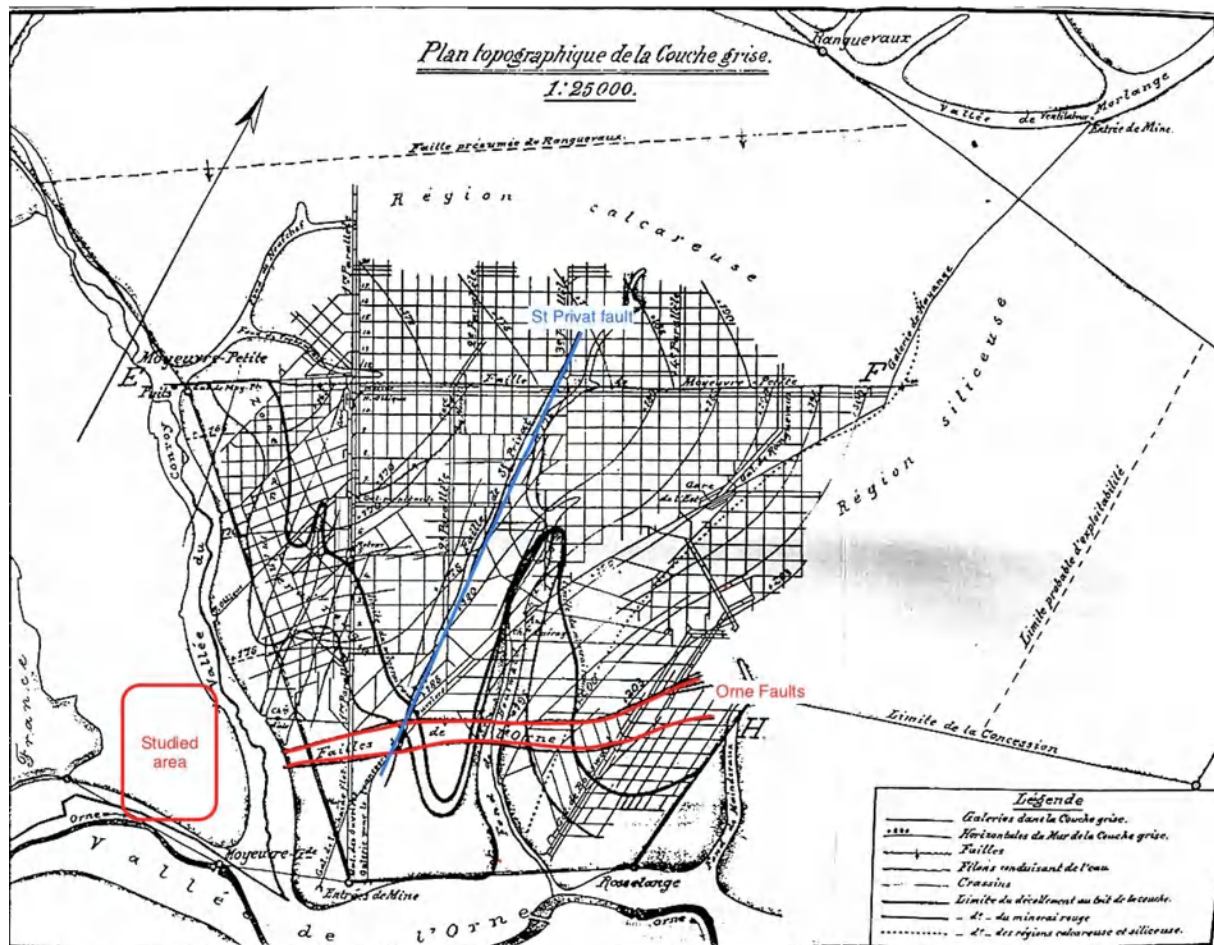


Figure 10. Historical document representing the surroundings of Moyeuvre-Grande with the location of fault zones whose orientations are consistent with those of the discontinuities observable in the virtual model (Spanier, 1914)

5 Part 3 - Geomechanical analysis

Students are led to question the long-term stability of the mine. For purely educational reasons, they are asked to propose reinforcement solutions for securing the mine, to avoid any consequence for the surface or underground.

The risk for the surface is essentially that of overall instability (rupture of the pillars due to overload) or a sinkhole (not studied by the students). The risk underground is essentially that of blocks falling from the roof.

To analyze the risk of overall instability, students must map the surfaces composed of in-place rock and those composed of embankments (Figure 11). The measurement of the exploited surfaces makes it possible to calculate the extraction ratio of the mine (exploited surface/total surface) with values around 50 to 60% when the embankments are considered equivalent to the rock in place (hypothesis 1) and 70 to 80% when the embankments are considered equivalent to exploited surfaces and therefore unsuitable to support the vertical loads in the long term (hypothesis 2). Considering the volumetric weight of the overburden around 25 kN/m³ (safety hypothesis integrating the presence of iron in the overburden) and a depth varying from 20m in the South to 55m in the North (Figure 12), the average stress in the pillars is then variable from 1.25 to 2.8 MPa (hypothesis 1) or from 2.5 to 6.8 MPa (hypothesis 2). The long-term resistance of the pillars is also estimated at 7.5 MPa on the basis of inverse analyses carried out on examples of collapsed zones in the Lorraine iron basin (this data is given to the students). This analysis leads students to question the interpretation of a safety coefficient which then varies from 2.7 (hypothesis 1) to 1.1 (hypothesis 2). The observation of the degradation of the pillars and vertical cracking in the embankments encourages us to favor hypothesis 2 and therefore conclude in a stable

situation, without excess security. Some reinforcements with masonry walls and pillars could be suggested for the most critical zones.

To analyze the risk of local instability, students are asked to propose a solution for reinforcement by bolting. Based on a set of pull-out tests carried out on bolts (Figure 13), students are required to calculate the bolt length and the required bolt density to secure the roof. The dimensions of the roof blocks delimited by discontinuities are of the order of 5 m² and the thickness of the blocks on the ground can reach 50 cm. A bolting plan with a mesh size of around 2m would then lead to 0.25 bolts per m². The load to be supported per bolt would then be approximately 50 kN, which implies an anchoring length of at least 60 cm and therefore bolts of at least 1.1m.

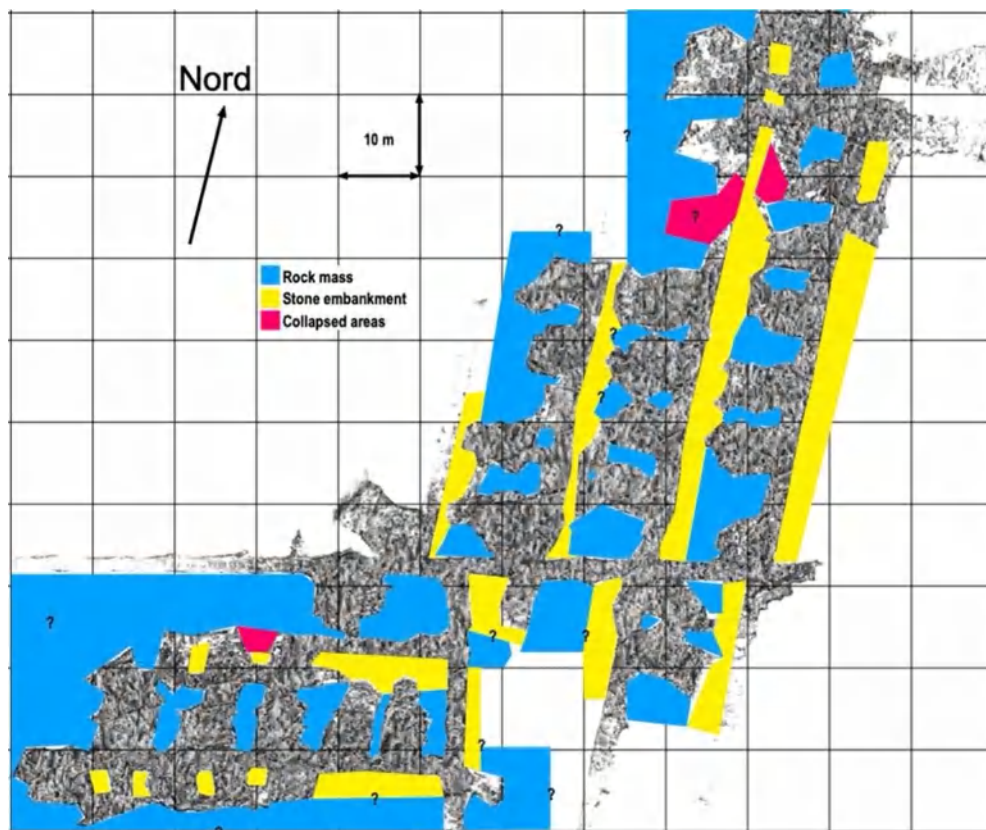


Figure 11. Identification of areas consisting of bedrock or fill

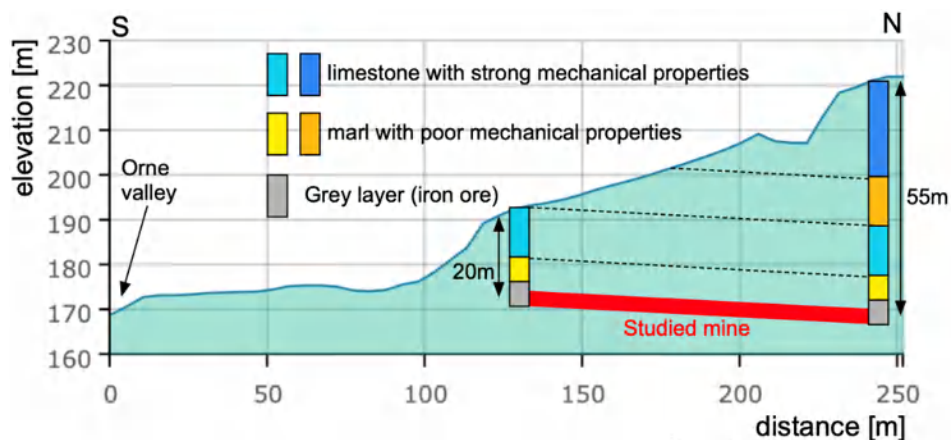


Figure 12. NS section directly above the studied area and schematic representation of the geology of the covering

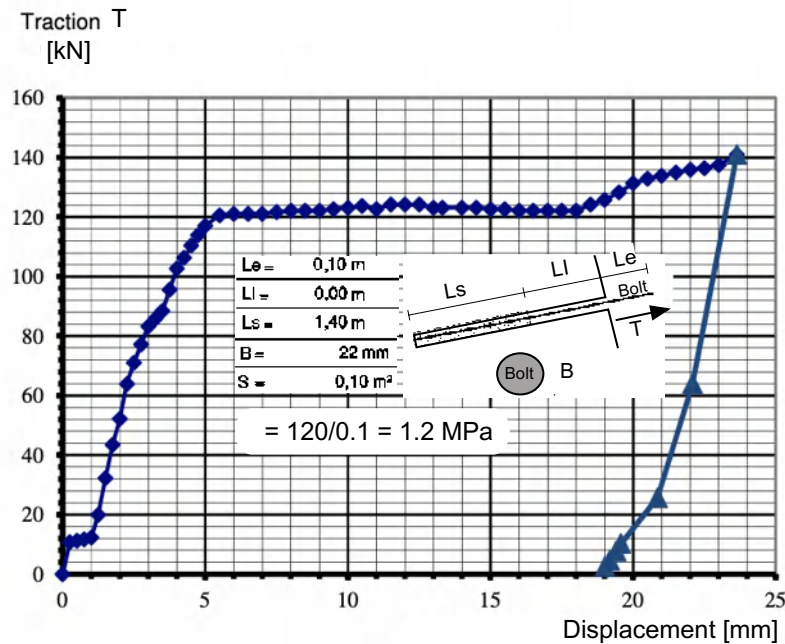


Figure 13. Example of a pull-out test carried out on a bolt

6 Students' feedback and recommendations

Examples of students' feedback are given next:

- "The concept is original, but it's still a very dense practical exercise. Nothing overwhelming, and the explanations are clear, but it's still a bit apprehensive at first."
- "The practical exercise is complex, therefore long, but very interesting."
- "Perhaps there are a few too many documents and information that we don't know how to use properly. As a result, we tend to focus on things that aren't necessarily very relevant."

"I find there's a lot of information, and it's sometimes difficult to make connections between them."

First, it appears that the use of virtual reality is perceived as an original and rather stimulating approach. Since the tool is easy to use, getting started didn't seem to pose any difficulties, allowing the students to focus on the substance of the subject.

The scope of the work to be completed and the amount of documents available is clearly unsettling. However, this corresponds to a realistic professional situation when an engineer must conduct an expert assessment: gathering disparate information, analyzing the situation to identify issues, and delving deeper into topics identified as critical. Exposing students to this situation, although disconcerting, seems appropriate for developing this type of skill. However, the instructor must find the right balance between allowing too much autonomy, at the risk of overwhelming the students, and overly regulating the activity, at the risk of receiving only a simple copy of what was explained. Students can typically waste unnecessarily time calculating precise values of the extraction ratio, when a simple approximative evaluation already allows them to guide their thinking. The same goes for the depth of exploitation and the calculation of bolting.

Finally, it should be noted that this exercise allows students to demonstrate originality in the analysis of documents by providing arguments that the teacher had not necessarily identified or by using original computer tools (calculation of surfaces automatically from image processing, for example).

The development cost of the 3D model was about 10k€ that include 2 days of field recording with 1 engineer and one technician from a specialized company (IGECAV). The economic profitability of the 3D model may then be estimated to be about 10 years. The main interest is the complementarity of such an activity with more classical practical or academical works in class. It allows to develop skills that are required for geotechnical expertise, with some practical application geological and geotechnical concepts.

7 Conclusions

The tool created allows students to be placed in a geotechnical expertise situation combining a visit to a remote environment presenting risks and consultation of a set of technical documents.

The required work appears destabilizing to them at first glance due to the large quantity of information and the novelty of the problem. It then appears important to guide them in carrying out each step in order to arrive at a first approximative answer. Personal work after the session is required for precisising some results and for writing the final report.

Acknowledgments

This model was produced with funding from the Grand-Est region and the Ecole Nationale Supérieure des Mines de Nancy, France. The measurements and 360° pictures were carried out by the company IGECARV. The choice of the site was possible thanks to the assistance of INERIS and GEODERIS, with the authorization of the municipality of Moyeuvre-Grande.

References

- Afsharipour, M., Maghoul, P. (2024). Towards education 4.0 in geotechnical engineering using a virtual reality/augmented reality visualization platform. *Geotechnical and Geological Engineering*, 42(4), 2657-2673.
- García-Vela, M. T., Borja-Bernal, C. P., Jordá-Bordehore, L., Medinaceli-Torrez, R., Loaiza, S., Falquez, D. A. (2021). Teaching rock mechanics using Virtual Reality: laboratory practices and field trips during the confinement of the Coronavirus COVID-19 in Ecuador, Bolivia, and Spain. In *IOP Conference Series: Earth and Environmental Science* (Vol. 833, No. 1, p. 012172). IOP Publishing.
- Gürsoy, M., & Buyuksagis, I. S. (2024). Virtual Reality in Underground Mining Education: Enhancing Machinery Comprehension. *Mining, Metallurgy & Exploration*, 41(6), 3073-3081.
- Janiszewski, M., Uotinen, L., Merkel, J., Leveinen, J., Rinne, M. (2020). Virtual reality learning environments for rock engineering, geology and mining education. In *ARMA US Rock Mechanics/Geomechanics Symposium* (pp. ARMA-2020). ARMA.
- Spanier J.P. (1914). Histoire des mines de Moyeuvre, document manuscrit.

Author's bio

Olivier Deck, University of Lorraine (FRANCE)

Prof. Olivier Deck is a full professor at the Nancy School of Mines, head of the Geosciences & Civil Engineering department. He carries out his research in the field of soil-structure interaction, reliability of structures and mechanical behavior of geotechnical structures. He is involved in teaching related to underground works such as mines, quarries and civil engineering tunnels with different use of 3D virtual applications.

Faculty perceptions and usage of generative AI in geotechnical engineering education

E. Salifu¹, A. Cuccurullo² & S. Muguda³

¹Arizona State University, Tempe, United States of America
emmanuel.salifu@asu.edu

²Université libre de Bruxelles, Brussels, Belgium
alessia.cuccurullo@ulb.be

³Durham University, Durham, United Kingdom
sravan.muguda-viswanath@durham.ac.uk

ABSTRACT: Artificial intelligence (AI) has played a growing role in geotechnical engineering, evolving from early applications in material modeling and data interpretation to modern generative AI (GenAI) systems capable of automating workflows and enhancing education. The integration of GenAI in geotechnical engineering education presents both opportunities and challenges. While recent studies highlight GenAI's potential in problem-solving, instructional support, and professional practice, concerns remain regarding its reliability, impact on cognitive development, and implications for faculty roles. This study examines faculty perspectives on GenAI adoption in geotechnical education, focusing on their familiarity with AI tools, institutional policies, and its influence on teaching and assessment. A survey of academics from various institutions worldwide revealed varying levels of engagement, with 92% of respondents currently not using GenAI in teaching but showing openness to future integration. Faculty concerns include over-reliance on AI for learning, the need for evolving assessment methods, and the accuracy of AI-generated content. Despite these challenges, 81% of respondents recommended or strongly recommended GenAI to their academic peers. Findings suggest that GenAI should be integrated as a complementary tool rather than a replacement for traditional teaching methods, with clear institutional policies and training initiatives to support responsible use. As AI technologies continue to evolve, fostering AI literacy among educators will be essential to maximize its benefits while mitigating risks to academic integrity and cognitive development.

Keywords: *Generative AI, Geotechnical education, Academic perspective*

1 Introduction

Artificial intelligence (AI) has been applied in geotechnical engineering for decades, beginning with traditional AI and neural networks. Early research, including studies by Chan et al., 1995; Ghaboussi et al., 1991; and Zhou & Wu, 1994, explored the use of neural networks for material behavior modeling, site investigation data interpretation, and pile driving analysis. In recent years, advancements in machine learning (ML) and explainable AI models have expanded AI's role in geotechnical engineering, particularly in geotechnical reliability analysis and hazard prediction (Abdollahi et al., 2024; Chai et al., 2024; Ge et al., 2024; Zhang et al., 2023). The latest phase in AI's evolution—Generative AI (GenAI)—is now being investigated for its potential to automate geotechnical workflows and transform educational practices (Baghbani et al., 2022; Chai et al., 2024; Reddy and Janga, 2025).

GenAI represents a distinct category of AI that extends beyond traditional data analysis and pattern recognition to generate human-like content, including text, code, sound, simulations, 3D objects, images, and videos. It builds on Generative Adversarial Networks (GANs) (Goodfellow et al., 2014) and

draws from large datasets to produce contextually relevant outputs based on user input. Since the launch of ChatGPT in November 2022, numerous other GenAI platforms have emerged, including Magic Write, Claude, Eleven Labs, Microsoft Copilot (formerly Bing Chat), Google Gemini (formerly Bard), DALL·E, Midjourney, Stable Diffusion, Channel, Musico, LLaMA, DeepSeek, Sora, Symphony Creative Studios, Mistral AI's Le Chat, and IBM Watsonx, with new platforms continuing to emerge. At the time of writing this article, OpenAI's 'deep research' model was released as part of a suite of models heralding the era of Agent Based GenAI (AGI) with applications in engineering education. The use of GenAI in geotechnical engineering education and practice is expanding, reflecting broader trends in AI adoption across various disciplines.

Recent studies have examined the role of GenAI in geotechnical engineering and related fields. Shoemaker et al. (2023) evaluated ChatGPT's capabilities by prompting it to answer National Council of Examiners for Engineering and Surveying (NCEES) civil and geotechnical practice exam questions, write a geotechnical data report, develop a Python function to calculate ultimate bearing capacity, and evaluate liquefaction potential using CPT values. Their findings suggest that GenAI tools could serve as virtual geotechnical engineering assistants, addressing labor shortages and supporting professionals in handling complex engineering tasks. Similarly, Reddy and Janga (2025) conducted an online survey to gather qualitative insights into the use of GenAI in education, research, and professional practice within the geotechnical and geoenvironmental engineering community. Their study surveyed faculty, students, industry practitioners, and professionals, capturing perspectives on GenAI's applications and limitations. While these studies highlight GenAI's ability to assist with data processing and engineering problem-solving, they also identify challenges related to specialized training requirements and the reliability of AI-generated outputs.

In higher education, GenAI is reshaping traditional instructional approaches (Peres et al., 2023). Although concerns persist about AI replacing human educators, research suggests that GenAI complements rather than replaces instructors. Chan & Tsi (2024) surveyed university faculty and students, finding that while GenAI can support teaching and administrative tasks, educators remain essential due to their critical thinking, emotional intelligence, and ability to engage students in meaningful learning – qualities AI lacks. Likewise, a scoping review by Xia et al. (2024) identifies GenAI's growing role in assessment, self-directed learning, and real-time feedback generation. However, their study also raises concerns about academic integrity and the need for institutions to reconsider assessment strategies in response to AI-driven changes. These findings suggest that GenAI's adoption in education should be approached carefully, so it supports rather than diminishes the role of instructors.

Despite these advancements, faculty engagement with GenAI in geotechnical engineering education remains largely unexplored. Understanding how educators perceive and apply these tools is important for curriculum development, instructional strategies, and faculty training, equipping instructors to integrate AI in ways that contribute meaningfully to student learning. Faculty perspectives also provide insight into ethical concerns, data privacy considerations, and accessibility challenges, which influence responsible AI adoption in academic settings. Examining faculty engagement further allows for a deeper understanding of student learning outcomes, helping shape more effective instructional practices that align with evolving educational needs.

This study takes a first step toward addressing this gap by examining faculty familiarity with GenAI applications, the ways in which these tools are used, and their impact on geotechnical engineering pedagogy. The following sections provide an outline of the methodology used in this study, overview of selected institutional policies on GenAI, and other findings on faculty interaction with GenAI tools in the context of geotechnical engineering education.

2 Academic perspective survey

Reddy and Janga (2023) conducted an online survey in 2023 to gather qualitative insights into the use of Generative AI in education, research, and professional practice within the geotechnical and geoenvironmental engineering community. The survey engaged faculty, students, industry practitioners, and professionals, eliciting their perspectives on the application of Generative AI in their respective domains. The study identified key benefits and limitations associated with the use of Generative AI across these sectors.

Building on this approach, the present study employed a similar online survey methodology, but with a specific focus on capturing the academic perspective within the geotechnical community regarding the use of Generative AI in teaching. The survey was directed exclusively at academics and was disseminated among the authors' professional networks, including individuals with experience in teaching geotechnical courses at the undergraduate or postgraduate level. To facilitate candid and unbiased responses, participation was voluntary and anonymous. The survey instrument was designed to evaluate academics' familiarity with diverse teaching methodologies, their understanding of AI and its associated tools, institutional policies on AI, the influence of AI on their pedagogical practices, and their perceptions of how Generative AI affects student learning.

A total of 24 respondents fully completed the survey (Figure 1). Among them, all but one currently hold permanent academic positions across various universities worldwide. These institutions are located in the United Kingdom, China, India, France, Belgium, Italy, Fiji, Iran, Sri Lanka, the United States of America, and Nigeria, reflecting a broad geographical representation. The survey participants came from diverse career stages, ranging from early-career academics to senior faculty members, providing a well-rounded perspective on the topic under investigation. Additionally, approximately 20% of the respondents identified as female, highlighting the gender composition within the surveyed academic cohort.

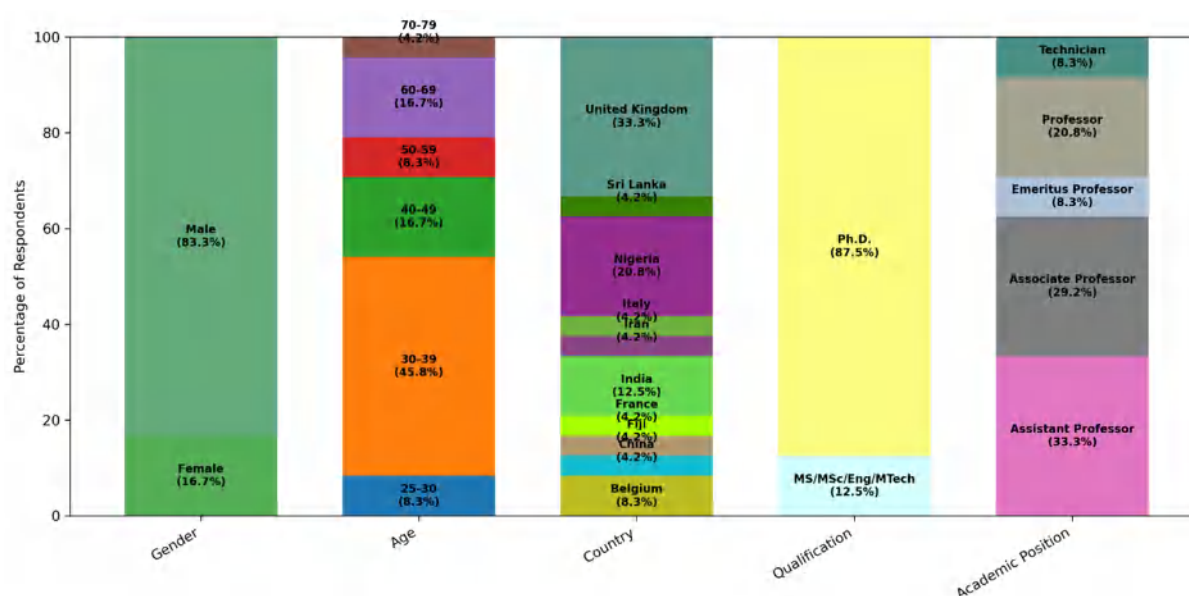


Figure 1. Distribution of respondents by academic position, age, country, gender, and qualification

3 Institutional policies on GenAI

There is a growing interest in generative AI within the civil engineering community, both in professional practice and academic education. Universities across Europe, the UK, and the USA are actively formulating policies to regulate the integration of generative AI tools in education, particularly concerning student engagement. The overarching aim seems to be to capitalise on AI's potential to enhance learning while simultaneously upholding academic integrity and ethical standards.

In the UK, the Russell Group, which represents 24 leading universities, has established key principles that promote AI literacy, ensuring that both staff and students are equipped with the requisite knowledge to use AI responsibly. These guidelines also encourage the adaptation of teaching and assessment methods to facilitate ethical and equitable AI integration (Russell Group, 2023). Institutions such as the University of Oxford, Imperial College London, and Durham University have introduced specific policies that advocate for responsible AI use, emphasising its role in augmenting—rather than replacing—critical thinking and independent learning (University of Oxford, 2024; Imperial College London, 2024).

In the United States, universities have adopted varied approaches towards the integration of generative AI in education. Some institutions, such as Cornell University and Columbia University, have delegated decision-making authority to individual academics, allowing them to determine the extent to which AI

tools are incorporated into their teaching. Conversely, Colorado State University has imposed restrictions on generative AI usage in line with its interim policy (Wall Street Journal, 2024). In contrast, Arizona State University and California State University have actively encouraged AI adoption in educational settings, recognising its potential to enhance student engagement and learning experiences. Notably, both institutions have partnered with OpenAI to integrate ChatGPT for personalised learning across their campuses, signalling a major shift towards AI-driven education (Graziano, 2024; Reuters, 2025).

Across Europe, prominent institutions such as ETH Zurich, Université Libre de Bruxelles, and the University of Copenhagen have begun implementing frameworks that foster AI-driven innovation while maintaining rigorous academic standards (ETH Zurich, 2024). These universities highlight the importance of continuous policy evaluation and refinement to keep pace with rapid technological advancements, ensuring that AI remains a tool for enhancement rather than a compromise to academic excellence.

Findings from our survey (more details below) indicate that academics in the UK, USA, and Europe generally possess awareness of the existence of their respective institutional policies on generative AI, which primarily advocate for responsible usage. However, a considerable number of respondents from institutions in Nigeria, India, and Sri Lanka reported that their universities had not yet established policies governing the use of AI tools in education for either staff or students. Additionally, respondents from Fiji noted that their institution had implemented a stringent policy that strictly prohibits the use of generative AI in any educational capacity. Interestingly, the survey also revealed that many academics, despite being aware of generative AI tools, were unfamiliar with their own institution's policies on their usage.

These findings highlight the significant divergence in AI policies across higher education institutions worldwide. While some universities have embraced AI integration and are actively shaping policies to regulate its use, others lack any formal guidelines, resulting in inconsistencies in how AI is perceived and utilised in education. The absence of standardised policies across different regions suggests the need to normalise regulations on generative AI usage to ensure a uniform educational framework that maintains comparable academic standards globally. As AI continues to evolve, establishing well-defined, universally recognised guidelines will be crucial in fostering equitable access to AI-enhanced learning while safeguarding academic integrity and innovation.

4 Survey results and discussion

4.1 Familiarity with Generative AI Apps

The results of the survey reveal a range of familiarity and engagement with GenAI among respondents. Participants indicated that they are either not familiar with GenAI or have only a basic understanding of its functionality, suggesting that there is a gap in awareness and exposure to the technology, probably from a lack of exposure to new technology or perhaps from the rapidly changing nature of AI developments. A portion of respondents (50% of individuals surveyed) expressed openness to learning more but admitted to having little understanding of how AI works, highlighting a need for clearer communication and education on its practical applications. A group of individuals (45% of individuals surveyed) reported being somewhat familiar with GenAI but have not yet integrated it into their work or teaching, indicating potential for growth with hands-on experience. As shown in Figure 2a, 92% of individuals surveyed declared that they do not use any GenAI Apps for their teaching activities. On the other end of the spectrum, a few respondents (8% of individuals surveyed) stated that they currently use GenAI and its capabilities, mostly for improving readability of academic text, for improving visualisation of graphs and data representations, for developing part or entire portions of lecture notes or for generating feedback reviews for student projects. Some acknowledged that there is still room for deeper exploration of advanced features. Interestingly only 5% of individuals surveyed do not intend to use GenAI in the future (Figure 2b).

(a) Use of Generative AI Apps for teaching (b) Intention to use Generative AI in the future



Figure 2. Survey results: (a) current use of Generative AI Apps for teaching and (b) intention to use Generative AI in the future.

Respondents indicated that the most commonly used Generative AI applications are ChatGPT, Google Gemini, and Co-Pilot. Their popularity can be attributed to several factors, such as their user-friendly interfaces and widespread availability, making them accessible to a broad audience. Additionally, they offer free access with optional premium plans, allowing users to explore their capabilities before committing to a subscription. Notably, Co-Pilot appears to be particularly favored, likely due to its seamless integration with Microsoft Office products, making it a preferred choice among professionals. Similarly, Google Gemini benefits from being embedded within Google's ecosystem, enhancing its appeal to users already familiar with Google's suite of tools.

Additionally, institutions appear to be proactively addressing AI integration, with almost half of the participants highlighting guidance for departments to develop their own policies for GenAI use. The fact that the university provides guidance for departments to create their own policies shows a proactive approach toward managing AI technologies. It also suggests that the institution is recognizing the need for regulation or best practices in the face of new AI technologies, ensuring that departments are informed and aligned with institutional goals while safeguarding ethical considerations and academic integrity. It is important to note that the majority of survey participants (67%) were either unsure (29%) or confirmed the absence (38%) of existing institutional or university policies or recommendations. The majority of participants also recognized the growing importance of GenAI, predicting that its role in education and professional fields will continue to expand in the coming years, underscoring the need for ongoing training and support. This forward-looking perspective suggests an understanding that education and professional development in AI will be critical in adapting to technological shifts. Educational institutions and workplaces might want to prepare for this by planning long-term strategies to integrate AI training into curricula and professional development programs. In summary, these comments reveal a range of familiarity with generative AI, from complete unfamiliarity to more advanced usage. They highlight the varying levels of understanding and engagement that exist, suggesting that a tailored approach to learning and professional development will be required. Institutions and organizations can help bridge these gaps by offering resources, training, and support that cater to both those who are new to AI and those who are already proficient, ensuring that the benefits of GenAI are accessible to all.

4.2 Impact on teaching methods

On the teaching side, GenAI is proving to be a valuable asset in administrative and instructional tasks. Educators are increasingly utilizing GenAI to automate the creation of lesson plans, design assignments, and grade student work, which allows instructors to dedicate more time to interactive, student-centered teaching methods. Figure 3a and 3b illustrate respondents' opinions on GenAI as a teaching aid, and its impact on the role of teachers. A majority (63%) viewed GenAI as a valuable tool for assisting instruction, while 29% remained uncertain or had reservations. Only 8% found it not useful for teaching. Furthermore, 29% of respondents believed that Generative AI could negatively impact the role of teachers in the future, whereas the remaining 71% either disagreed (33%) or were unsure (38%).

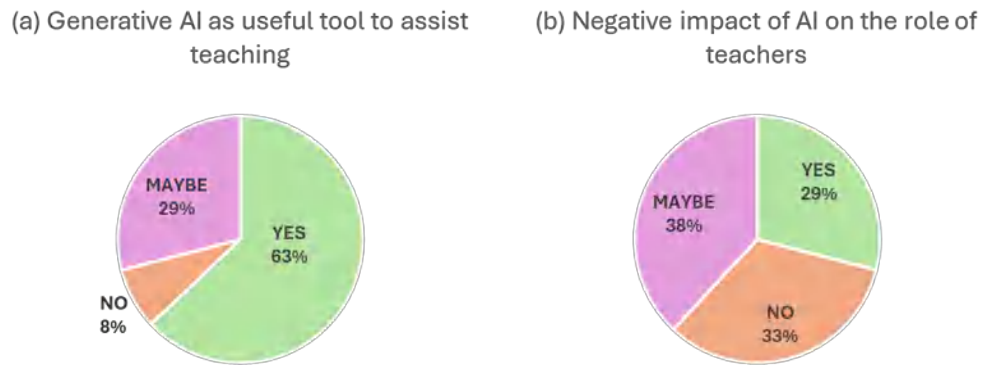


Figure 3. Survey results: (a) respondents opinion of generative AI as useful tool to assist teaching; (b) respondents opinion on negative impact of generative AI on the role of teachers in the classroom in the future.

As shown in Figure 4, survey participants mostly agree that GenAI can positively or extremely positively affect professional correspondence, academic writing and the redaction of course material. AI tools can generate simulations and case studies based on real-world scenarios, which are particularly beneficial in geotechnical engineering, where students can apply theoretical knowledge to practical problems. These AI-generated materials can also be personalized based on individual learning progress, creating a more adaptive and tailored educational experience for students. Despite these benefits, educators expressed concerns about AI's potential role in diminishing the development of essential skills such as critical thinking and problem-solving. Some expressed fear that over-reliance on AI could result in students who are less capable of approaching complex engineering challenges independently. A respondent recommended that “*Generative AI should be used as a tool [and] outputs must be critically evaluated. It should be used as an assistant rather than something that replaces intellectual work.*”

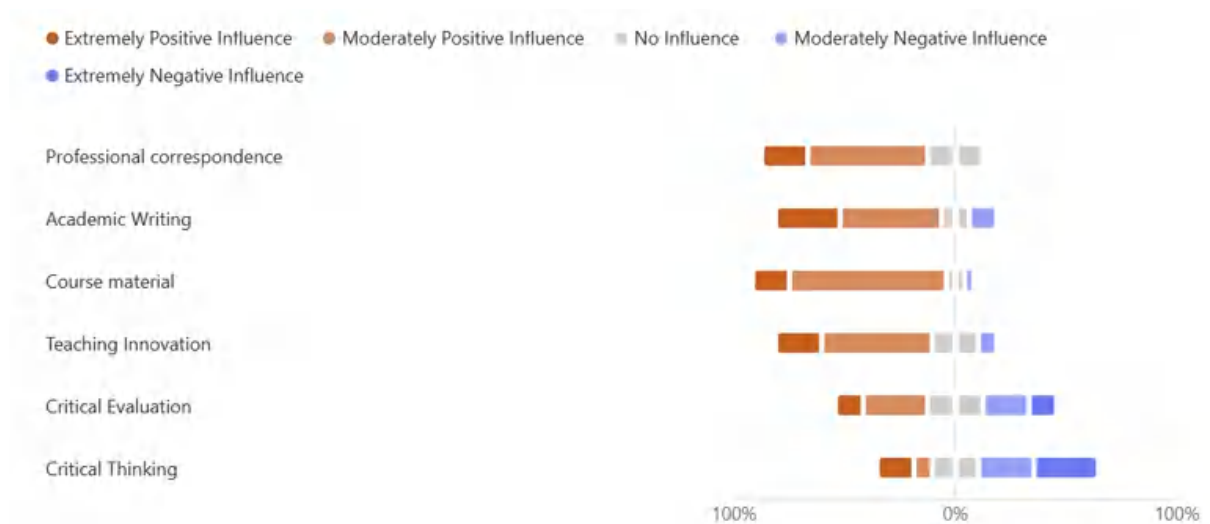


Figure 4. Survey results on the effect Generative AI has on one's teaching skills.

The challenge, therefore, lies in ensuring that AI tools are used as supplements to traditional methods rather than as replacements for fundamental educational practices. Educators also highlighted concerns about the accuracy and reliability of AI-generated content, especially in a technical field like geotechnical engineering, where precision is paramount. A respondent posited that “*Generative AI is quick but often incorrect (it generates information, not knowledge). Its accessibility will trump its accuracy*”. There is a risk that AI-generated resources might contain errors or lack the nuanced understanding required for highly specialized technical problems, potentially leading to misunderstandings or misapplications of core concepts. According to respondents, it is necessary to maintain a balance between AI-enhanced

learning and traditional problem-solving exercises by ensuring that AI-generated materials align with academic standards and do not oversimplify complex topics; and by detecting AI-generated assignments, as students may submit AI-assisted work without understanding the content.

The survey respondents emphasized the importance of ensuring that students are trained to critically evaluate AI-generated outputs, understanding the limitations and potential biases inherent in the technology. Institutions must provide clear guidelines and policies for the ethical use of AI in academic settings, including training students to use AI responsibly in both academic and professional contexts. AI should be viewed as a tool to enhance, rather than substitute, traditional learning methods, encouraging active learning through AI-assisted simulations rather than passive content consumption.

4.3 Challenges, considerations, and concerns

Survey participants raised several key concerns regarding the integration of GenAI into geotechnical engineering education and higher education in general. Despite worries about its potential negative impact on teachers' roles (Figure 3b: 38% "Maybe" and 29% "Yes"), a majority of participants (81%) still support its adoption, with 54% recommending and 27% strongly recommending its use to academic colleagues. Some of the concerns raised are summarized below.

Familiarizing Educators with Generative AI: There is a clear need for educators to understand both the capabilities and limitations of GenAI. Successfully integrating these tools into teaching requires time and careful adaptation, as they introduce both opportunities and challenges. The role of educators may shift from being the primary source of knowledge to a facilitator guiding students in the effective and responsible use of AI.

Impact on Human Cognitive Abilities: As GenAI assumes tasks traditionally performed by humans, concerns arise about its potential impact on cognitive development, critical thinking, and problem-solving skills. A survey participant explicitly said "*it [GenAI] will spoil the creativity of the user*". With the emergence of advanced GenAI models, such as OpenAI's Deep Research, which has the capability to generate full doctoral dissertations (Maynard, 2025), these concerns are both valid and increasingly relevant. As GenAI continues to develop more sophisticated reasoning abilities, there is a growing risk that novice users may engage with these tools before undergoing rigorous learning experiences, potentially hindering intellectual growth. The key challenge is finding a balance—leveraging AI for efficiency while ensuring students remain intellectually engaged in deep reasoning and deep learning. Over-reliance on AI for cognitive tasks may diminish mental agility, as deep learning, creativity, and overall intellectual development is typically expected to stem from struggle, discovery, and problem-solving.

Evolving Assessment Methods: Assessing in New Ways: Traditional assessment strategies may become less effective as GenAI can generate responses at a level comparable to top-performing students. This underscores the need to rethink how we evaluate learning. Relying solely on fact-based or recall-driven questions is no longer sufficient. Instead, assessments should emphasize critical analysis, creativity, and applied knowledge—areas where human insight remains essential.

Balancing Speed and Accuracy: While GenAI provides rapid access to information, its responses do not always guarantee accuracy. The convenience of AI-generated content may lead to over-reliance on speed at the cost of accuracy, increasing the risk of misinformation. Strong critical evaluation skills are required to verify the validity of AI-generated outputs.

The Urgency to Experiment: given the rapid development of generative AI, there seems to be a perceived urgency for educators to experiment with these technologies to fully understand their strengths, limitations, and ethical implications. This experimentation can provide valuable insights into how AI can complement traditional teaching methods and potentially unlock new ways of engaging with students.

It must be noted that these current perceptions, challenges, and concerns about usage of GenAI are based on the current state of the technology, academic exposures, and institutional policies. Considering that both academics and institutions across the globe are actively evaluating the impacts of AI in education, and the industry is constantly developing and updating the technologies, it is imperative that the academic exposure and institutional policies will change in future and subsequently even the academic perception on using it.

5 Conclusions

The integration of GenAI in geotechnical engineering education is at an early yet transformative stage, with the potential to enhance educational outcomes and reshape instructional approaches. However, its adoption must be carefully managed to ensure that AI serves as a complementary tool rather than a replacement for traditional learning. A balanced approach is essential, where students leverage AI for efficiency while maintaining the ability to think critically and solve problems independently. Survey findings indicate both enthusiasm and caution among faculty, highlighting the need for structured AI adoption strategies that prioritize responsible use, faculty training, and evolving assessment methods to align with AI-driven learning environments. Educational institutions should actively foster AI literacy, equipping students with the skills to use AI tools effectively, critically assess outputs, and refine their understanding. This involves integrating AI literacy into curricula, ensuring ethical and informed usage while maintaining rigorous academic standards. Key concerns include the potential over-reliance on AI for problem-solving, the accuracy of AI-generated outputs, and its long-term impact on cognitive development and student engagement. However, when thoughtfully implemented, GenAI can support instructional tasks, streamline administrative processes, and enhance student learning experiences. As AI adoption expands, institutions must establish clear guidelines, ethical frameworks, and targeted professional development programs to equip educators with the skills needed to navigate this technological shift. Additionally, further research into GenAI's long-term effects on cognitive development, academic assessments, and professional growth will be crucial in shaping its role in geotechnical education. As technological advancements continue to evolve, educational practices must adapt accordingly, ensuring that future engineers are well-prepared for an increasingly automated and data-driven world.

Acknowledgements

The authors acknowledge the use of ChatGPT and Microsoft Copilot in refining aspects of this manuscript, including improving readability, clarity, and grammar. The final content was reviewed and edited by the authors for accuracy. We extend our sincere gratitude to all survey participants who contributed their time and insights, providing valuable perspectives on the integration of GenAI in geotechnical engineering education. Their input was instrumental in shaping the findings of this study.

Survey Form & Data

The survey form is available at: <https://forms.office.com/e/08Ci74T8Z1>. The data used in this study is available upon request.

References

- Abdollahi, A., Li, D., Deng, J., Amini, A. (2024). An explainable artificial-intelligence-aided safety factor prediction of road embankments. *Engineering Applications of Artificial Intelligence*, 136, 108854.
- Baghbani, A., Choudhury, T., Costa, S., Reiner, J. (2022). Application of artificial intelligence in geotechnical engineering: A state-of-the-art review. *Earth-Science Reviews*, 228, 103991.
- Chai, P., Hou, L., Zhang, G., Tushar, Q., Zou, Y. (2024). Generative adversarial networks in construction applications. *Automation in Construction*, 159, 105265.
- Chan, C. K. Y., Tsi, L. H. Y. (2024). Will generative AI replace teachers in higher education? A study of teacher and student perceptions. *Studies in Educational Evaluation*, 83, 101395.
- Chan, W. T., Chow, Y. K., Liu, L. F. (1995). Neural network: An alternative to pile driving formulas. *Computers and Geotechnics*, 17(2), 135–156.
- ETH Zurich (2024). Artificial Intelligence in Education. Available at: <https://ethz.ch/en/news-and-events/artificial-intelligence-in-education.html> [Accessed 14 February 2025].

- Ge, Q., Li, J., Lacasse, S., Sun, H., Liu, Z. (2024). Data-augmented landslide displacement prediction using generative adversarial network. *Journal of Rock Mechanics and Geotechnical Engineering*, 16(10), 4017–4033.
- Ghaboussi, J., Garrett, J. H., Wu, X. (1991). Knowledge-Based Modeling of Material Behavior with Neural Networks. *Journal of Engineering Mechanics*, 117(1), 132–153.
- Goodfellow, I., Pouget-Abadie, J., Mirza, M., Xu, B., Warde-Farley, D., Ozair, S., Courville, A., Bengio, Y. (2014). Generative Adversarial Nets. In Ghahramani et al. (Eds.), *Advances in Neural Information Processing Systems* (Vol. 27). Curran Associates, Inc. Available at: https://proceedings.neurips.cc/paper_files/paper/2014/file/5ca3e9b122f61f8f06494c97b1afccf3-Paper.pdf.
- Graziano, R. (2024). ASU leaders explain university's relationship with OpenAI. *The State Press*, 3 April. Available at: <https://www.statepress.com/article/2024/04/openai-april-2024-update> [Accessed 14 February 2025].
- Imperial College London (2024). Artificial Intelligence Policy. Available at: <https://www.imperial.ac.uk/education-office/artificial-intelligence-policy> [Accessed 14 February 2025].
- Maynard, A. (2025). Can AI Write Your PhD Dissertation?. Available at: <https://futureofbeinghuman.com/p/can-ai-write-your-phd-dissertation> [Accessed 14 February 2025].
- Peres, R., Schreier, M., Schweidel, D., Sorescu, A. (2023). On ChatGPT and beyond: How generative artificial intelligence may affect research, teaching, and practice. *International Journal of Research in Marketing*, 40(2), 269–275.
- Reddy, K. R., Janga, J. K. (2025). Utilization of generative artificial intelligence in geotechnical and geoenvironmental engineering. In Agnihotri, A. K. R., Reddy, B. A. (Eds.), *Sustainable Infrastructures* (pp. 241–267). Springer Nature Singapore.
- Reuters (2025). OpenAI Targets Higher Education in the U.S. with ChatGPT Rollout at California State University. Available at: https://www.reuters.com/technology/openai-targets-higher-education-us-with-chatgpt-rollout-california-state-2025-02-04/?utm_source=chatgpt.com [Accessed 14 February 2025].
- Russell Group (2023). Russell Group Principles on the Use of Generative AI in Education. Available at: https://russellgroup.ac.uk/media/6137/rg_ai_principles-final.pdf?utm_source=chatgpt.com [Accessed 14 February 2025].
- Shoemaker, T. A., Beaino, C., Centella, R. D. M., Zhao, W., Tanissa, C., Lawrence, J., Hashash, Y. M. A. (2023). Generative AI: The new geotechnical assistant? *Journal of Geotechnical and Geoenvironmental Engineering*, 149(10).
- University of Oxford (2024). AI Guidance for Students and Staff. Available at: <https://www.ox.ac.uk/news-and-events/ai-guidance> [Accessed 14 February 2025].
- Wall Street Journal (2024). Inside Universities' Love-Hate Relationship with ChatGPT. Available at: https://www.wsj.com/articles/inside-universities-love-hate-relationship-with-chatgpt-92808293?utm_source=chatgpt.com [Accessed 14 February 2025].
- Zhang, W., Gu, X., Hong, L., Han, L., Wang, L. (2023). Comprehensive review of machine learning in geotechnical reliability analysis: Algorithms, applications and further challenges. *Applied Soft Computing*, 136, 110066.
- Zhou, Y., Wu, X. (1994). Use of neural networks in the analysis and interpretation of site investigation data. *Computers and Geotechnics*, 16(2), 105–122.

Authors' bios

Emmanuel Salifu, Arizona State University (United State of America)

Dr. Emmanuel Salifu is an Assistant Professor in the School of Sustainable Engineering and the Built Environment at Arizona State University and a Senior Investigator at the Center for Bio-mediated and

Bio-inspired Geotechnics (CBBG). As pioneer of Fungi Geotechnics and Principal Investigator of the Nature-Inspired Interdisciplinary Sustainable Engineering (NISE) Lab, his research advances biologically inspired and nature-based engineering solutions to enhance infrastructure resilience, climate adaptation, and disaster mitigation. His expertise spans bio-geotechnical engineering, soil erosion mitigation, contaminant remediation, and environmental impact analysis. His work integrates geotechnical, biological, and environmental engineering with biotechnology to develop innovative solutions for ground improvement, dust mitigation, and sustainable land management. Dr. Salifu teaches geotechnical, biogeotechnical, and geoenvironmental engineering at undergraduate and graduate levels. His teaching philosophy emphasizes interdisciplinary problem-solving, critical-thinking, sustainability, and engineering intuition, equipping students with the skills to address real-world challenges. He actively mentors undergraduate, master's, and Ph.D. students.

Alessia Cuccurullo, Université libre de Bruxelles (Belgium)

Dr. Alessia Cuccurullo holds a dual International Ph.D. in Civil Engineering from the University of Pau and Adour Countries (France) and Durham University (UK). She was a Marie Skłodowska-Curie Fellow in the TERRE Innovative Training Network, where she contributed to the development of novel geotechnologies aimed at enhancing the competitiveness of the European construction industry while promoting a low-carbon agenda. Dr. Cuccurullo has extensive experience in soil mechanics, sustainable building materials, earthen construction, and soil improvement using lime, cement, induced calcite precipitation and alkali activation. Her research focuses on advancing environmentally friendly construction practices and optimizing soil stabilization techniques for sustainable infrastructure. She is currently an Assistant Professor at Université libre de Bruxelles (ULB), where she teaches Soil Mechanics and Geotechnical Engineering. In this role, she combines her research expertise with teaching to equip future engineers with the knowledge and skills necessary to develop innovative and sustainable solutions in geotechnical engineering. Additionally, she has supervised numerous BEng, MEng, MSc, and PhD projects, fostering innovation and contributing to the advancement of sustainable engineering practices.

Sravan Muguda, Durham University (United Kingdom)

Dr. Sravan Muguda is an Assistant Professor in Sustainable and Resilient Infrastructure at the Department of Engineering, Durham University. His expertise lies in bio-geotechnics, sustainable geo-infrastructure, and earthen construction materials. His research is strongly aligned with the United Nations Sustainable Development Goals (SDGs), particularly in advancing soil stabilization techniques, promoting resilient infrastructure, and developing climate adaptation strategies. Dr. Muguda's work focuses on creating sustainable geo-materials and bioremediation techniques, addressing key challenges related to sustainable cities and communities (SDG 11), climate action (SDG 13), and life on land (SDG 15). He actively integrates research with education, leading courses in surveying, environmental engineering, and design projects while incorporating innovative teaching methods to enhance student engagement. Additionally, he has supervised numerous BEng, MEng, MSc, and PhD projects, fostering innovation and contributing to the advancement of sustainable engineering practices in academia and industry.

PEGGHy - Platform for Experimental Geophysics, Geotechnics and Hydrogeology of the Graduate School of Geological Engineering, Nancy, France

J. Sausse^{1,2}, P. Cupillard^{1,2}, A. Abdallah^{1,3}, Y. Géraud^{1,2}, M. Diraison², C. Oltean^{1,2}, F. Golfier^{1,2} & O. Cuisinier^{1,3}

¹*École Nationale Supérieure de Géologie - Université de Lorraine, Vandœuvre-lès-Nancy, France*
judith.sausse@univ-lorraine.fr

²*GeoRessources - Université de Lorraine / INSU - CNRS, Nancy, France*
paul.cupillard@univ-lorraine.fr

³*LEMTA - Université de Lorraine / INSU – CNRS, Nancy, France*
adel.abdallah@univ-lorraine.fr

ABSTRACT: Students in geo-engineering need to master the complex structuring, properties and behaviours of the underground. In addition to geological observations, pedagogical field works can involve the deployment of instruments for dedicated measurements to characterize and monitor a specific site. However, surveys are often carried out with a limited knowledge on the geometry of the underground structure, so discussing the accuracy and limitations of the prospection methods in a robust and quantitative way is tricky. To circumvent this major issue, we have developed the Platform for Experimental Geophysics, Geotechnics and Hydrogeology (PEGGHy), which holds "artificial", fully controlled geological structures and heterogeneities. PEGGHy is filled with aggregates which have been selected based on i) their lithological properties so that significant geophysical contrasts are expected, and ii) their porosity and permeability to provide heterogeneous fluid flows. In addition, the base of the pit and the top of some folded layers are sealed by geomembranes to create both a confined reservoir and a free aquifer. Thanks to photogrammetric data acquired by drone, PEGGHy goes with a 3D, centimetric precision digital twin. Such a numerical tool allows to quantitatively compare models derived from geophysical, geotechnical and/or hydrogeological data with the true subsurface geometry. It also allows to run various modelling codes and confront their results to real data, providing a unique opportunity to teach and test numerical schemes, discretization algorithms and auscultation methods.

Keywords: *Experimental Platform, Applied geophysics, Geotechnical engineering, Hydrogeology, Digital twin*

1 Introduction

Engineers in geosciences need to master the complex structuring, properties and behaviours of the underground. To emphasize this complexity, all educational training in geosciences include "field" periods to acquire, describe, understand and model data from either natural or man-made environments. In addition to geological observations, field works can involve the deployment of instruments for dedicated measurements to characterize and monitor a specific site, estimate the associated risk and environmental issues, and support decisions of our future engineers.

Geophysical, geotechnical and hydrogeological measurements allow estimating petrophysical parameters of soil and underground materials. However, fieldwork and surveys in geosciences are often carried out with a limited knowledge on the geometry of the underground structure, so discussing the accuracy and limitations of the prospection methods in a robust and quantitative way is tricky. To

circumvent this major pedagogical issue, we have developed the Platform for Experimental Geophysics, Geotechnics and Hydrogeology (PEGGHy), which holds “artificial”, fully controlled geological structures and heterogeneities. The platform is located near the *École Nationale Supérieure de Géologie* (ENSG) campus at Vandœuvre-lès-Nancy, France. It has been conceived as part of a collaborative initiative by the ENSG teaching team, with significant contributions from faculty members overseeing the Applied Geophysics (authors: P. Cupillard, J. Sausse, Y. Géraud and M. Diraison), Hydrogeology (authors: F. Golfier and C. Oltéan) and Geotechnical Engineering (authors: A. Abdallah and O. Cuisinier) programs. This document reflects the pedagogical vision shared by the authors and, more broadly, by the ENSG teaching team.

In the first part, the content and the geometry of the PEGGHy geological units are presented. These units are equipped with optical fibers which are described in the second part. Then, the 3D digital twin of the platform derived from photogrammetric data of the construction site is detailed. Finally, the pedagogical perspectives that PEGGHy opens in terms of geotechnical and geophysical studies are discussed using examples. Because boreholes and piezometers are missing at this stage, hydrogeological aspects are not included.

2 Technical design of the platform

PEGGHy has been built in two steps: 1) the excavation of a 60m long, 20m wide and 2.5 to 4m deep pit, and 2) its finely controlled filling (i.e., using centimetric precision GPS) by a stack of various rock aggregates which mimics sedimentary layers of different lithological and petrophysical nature (Table 1). Some of the layers are horizontal whereas some others are folded. Moreover, they are shared between two compartments separated by a fault. Such a design leads to physical interfaces and a specific geometry representing main natural geological objects on a reduced but significant scale (Figure 1). The total excavated volume is of the order of 4 600 m³.

In addition to specific physical properties, the materials have been chosen with respect to the proximity of quarries to the project site, for both educational and ecological reasons:

- **Host carbonate rocks of ENSG site**

The ENSG site is built on Jurassic limestone, with very little vegetal soil on top of it. This formation consists of oolitic limestones of the “Polypiers inférieurs” (Bajocian). These are micritic and/or oolitic and bioclastic limestones stratified in horizontal beds with often oblique internal stratification. The limestones were excavated, crushed on site, and then placed back in the pit to build the base of a fold.

- **Alluvial siliceous sands of the Hériménil quarry (company Vicat)**

These are crushed siliceous alluvium corresponding to mix of sands and pebbles attributed to the Fxb3M alluvium. The Fxb3M alluvium has been extensively exploited along the Meurthe river valley. The deposits are highly sandy, with gravel and pebble fractions predominantly concentrated in the upper layers. The granite and gneiss constituents exhibit an advanced degree of weathering with widespread mineralogical alteration.

Two grain sizes have been selected: a fine one for a sandy aquifer formation (0-5 mm) and a coarser one (20-80 mm) for a water retention basin (30% porosity) for future hydrogeological testing.

- **Basaltic gravels « trapp » of the Raon l'Étape quarry (company Colas)**

The large quarry of Raon l'Étape exploits the basaltic “trapp” representative of Devonian to Lower Carboniferous calc-alkaline volcanism in the northern Vosges in France. Thanks to its specific hardness and mechanical properties, the rock, crushed on site, is used as ballast or in asphalt mixes for the rail track construction. The trapp formation corresponds to a porphyritic basalt.

- **Overlying clays from the carbonate quarry (company Humens)**

Humens operates an open-pit limestone quarry at Pagny-sur-Meuse, where clay materials are processed. The quarrying activities are organized around four main working faces, each ranging from 15 to 20 meters in height. The darker, impure limestones, enriched with siliceous components (clays), overlie the limestone strata. These are not currently exploited but are instead used for the gradual backfilling of the site to facilitate reforestation ('reclamation') after mining.

The various aggregates involve therefore clays, carbonates, siliceous alluvial deposits, and basic rocks. They were selected based on 1) their expected physical properties, with sufficient contrasts to provide

clear interfaces for the geophysical measurements, and 2) their porosity and permeability to allow for relevant fluid flow. Moreover, the base of the pit, down to 4 m, and the top of the fold are sealed by geomembranes (HDPE geomembrane) and a geobentonitic complex (NaBento – Geosynthetic Clay Liner - GCL), consisting of a sodium bentonite layer encapsulated between geotextiles, providing a low-permeability barrier.

Table 1. Aggregates and petrophysical properties that filled the various PEGGHy units.

Type and petrophysical properties of aggregates	Carbonates	Siliceous sands	Siliceous pebbles	Basaltic « trapp »	Clays
Volume	410 m ³	1 930 m ³	256 m ³	850 m ³	1 090 m ³
Granulometry	/	0/5 mm	20/80 mm	6.5/13 mm	0/5 mm
Aggregate Los Angeles abrasion test value	< 20	12-20	12-20	9-10	/
Aggregate micro-deval wear test	/	10-20	10-20	15-35	/
Porosity	/	/	30%	22%	20%
Hydraulic conductivity	/	1.6.10 ⁻⁴ m/s	/	/	10 ⁻⁸ m/s
Grain density	2.7	2.7	2.7	3.1	1.7
Aggregate density	/	1.6	/	2.4	/

3 Optical fiber instrumentation

Optical fiber measurement relies on the backscattering of a short (<10 ns) laser pulse injected into the fiber. The spatial distribution of the measured property, such as temperature, is determined using a highly accurate timing system that accounts for the velocity of light within the fiber.

Three types of optical fibers are installed: two at the bottom of the pit and the other near the surface. They all converge to an optical splice protection box which outputs the signals through a standard optical fiber cable equipped with various output ports so that different interrogator types can be used.

Sensitive optical fibers

Strain sensing and temperature sensing cables from our partner ANDRA (French national radioactive waste management agency) were installed at the bottom of the pit, enabling continuous recording of underground deformation and temperature associated to, e.g., water flow or mass loading at the surface. The pedagogical interest of such cables will be to provide real data to be compared to hydro-geomechanical simulations, showing students the significance of the different terms in the system of coupled equations and emphasizing numerical discretization issues.

Distributed acoustic sensing

A non-magnetic Distributed acoustic sensing (DAS) cable was supplied and installed by the SERCEL company at 15 cm depth within the platform. The Helically Wound Cable (HWC) has a very large cross-section (2 cm). It is a high-performance tool for monitoring both passive and active seismic vibrations, providing continuous records of the strain rate due to seismic waves propagating in the DAS cable direction (Zhan, 2020). Although challenges remain to make such data widely operable in the industry world, "DAS networks will inevitably complement classic seismic sensor deployment" (Nziengui-Bâ et al., 2023) for imaging the near-surface (Dou et al., 2017; Ajo-Franklin et al., 2019) in the future.

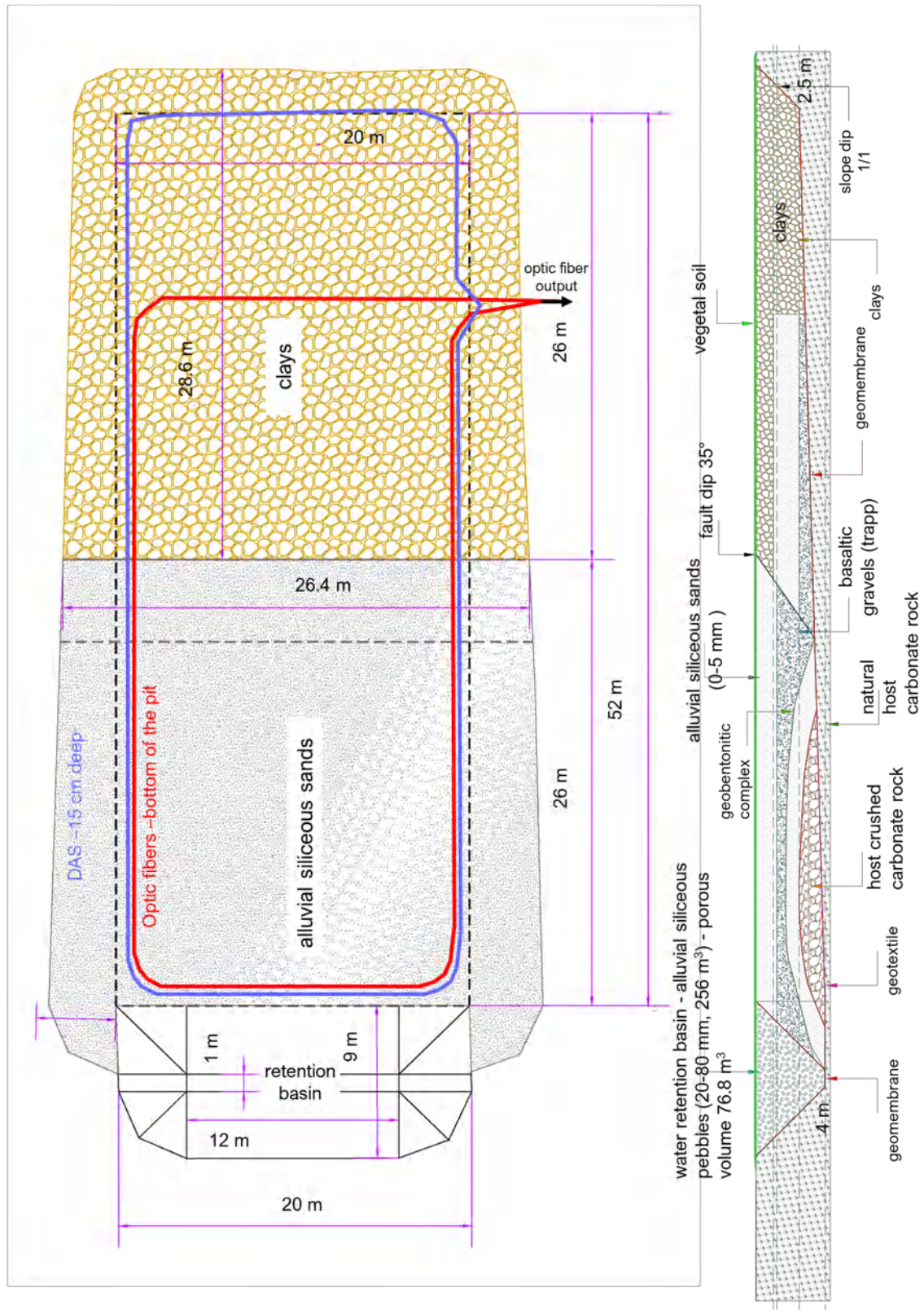


Figure 1. Technical drawings of the PEGGHy platform. Left: top view. Right: cross-section.

4 3D geomodelling – digital twin

Thanks to photogrammetric data acquired by drone, PEGGHy comes with a 3D digital twin. The dataset corresponds to 17 photogrammetric surveys acquired by Enerex SAS. Each survey was carried out at different times during the construction of the platform, so that it is possible to build a relevant, centimetric precision geomodel from the point clouds. Points were acquired using the European Terrestrial Reference System 1989 (EPSG 25832) coordinates and then turned into the RGF93 (EPSG 2154) coordinates to build the geomodel. This last coordinate system is 2D Cartesian along the East and North axes, and its unit is meter.

The 3D geomodeling is carried out using the Aspen-SKUATM geomodeler software. Several steps have been followed to build the triangulated surfaces of the model, with a 40 cm mesh resolution. The methodology relies on both the direct and indirect approaches described by Caumon et al. (2009) using the Discrete Smooth Interpolation (DSI) method (Mallet, 1992). The surfaces are explicit, meaning that their geometry is described by triangle meshes instead of iso-values of a 3D scalar field. The surfaces model the base of the platform, the physical interfaces between layers of various aggregates, and the faults (including the limit between the retention basin and the layers) (Figure 2).

The model is sealed, meaning that the connection of the surfaces (i.e., the topology) is properly controlled using border constraints. This allows to define volumes which corresponds to the different geological blocks of the platform. These volumes can be meshed with the desired resolution to perform numerical simulations of various phenomena such as seismic wave propagation, electrical potential field, fluid flow, and coupled hydro-geomechanical processes. Such simulations require physical property values. At this stage, only porosity, hydraulic conductivity and density values are known for a couple of blocks (Table 1). Other properties like elasticity coefficients, electrical resistivity or dielectric permittivity, could be estimated using inverse approaches.

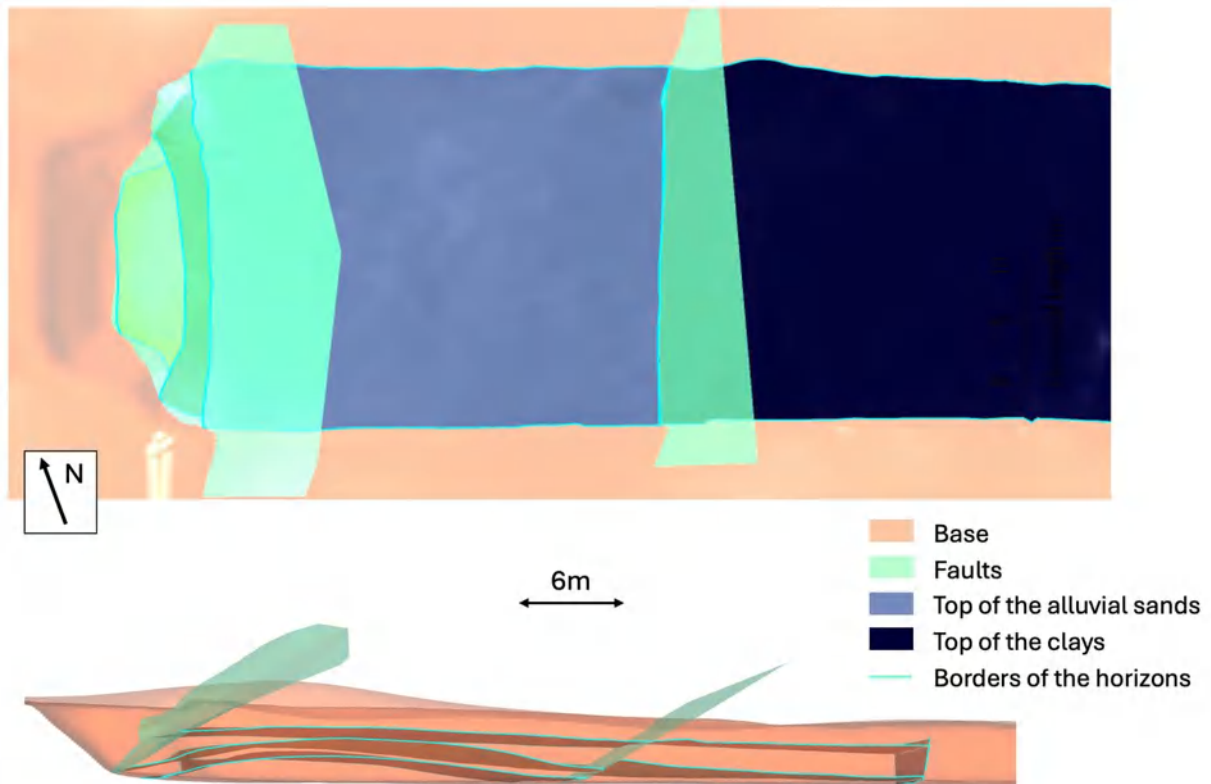


Figure 2. Top: map view of the PEGGHy digital twin. The topographic surface is hidden to exhibit the top of both the alluvial sands and the clays. Bottom: side view of the PEGGHy digital twin. All the horizons are shown except the topographic surface, the top of the shallower alluvial sands and the top of the clays. In the two parts of the figure, we let the fault surfaces extend above the topographic surface.

5 Some pedagogical perspectives for geotechnics and geophysics

A key educational objective in geotechnical engineering is to establish and manage the development of a "ground model", or geotechnical model as outlined by the Eurocode (EN 1997-2:2024. Eurocode 7 – Geotechnical design – Part 2: Ground properties. European Committee for Standardization, Brussels, 2024). This model represents both a conceptual and physical description of the subsurface conditions at a specific site. It plays a crucial role in understanding the geological and geotechnical characteristics of the ground, which directly affect the design and construction of structures.

To properly describe the geology of a site, a geotechnical model must integrate data from a variety of sources, including geological surveys, borehole logs, geophysical measurements, and laboratory tests. Geophysical methods, such as seismic refraction, ground-penetrating radar, and electrical resistivity surveys, offer valuable insights into the depth and nature of soil and rock layers beneath the surface. The geotechnical model not only reflects the vertical stratigraphy of the site but also incorporates lateral variations in geological formations. For example, the soil profile may shift from soft clay to dense sand at different points across the site. By considering these spatial variations, the model enables engineers to predict how the soil will behave under load, assess potential settlement, and identify risks such as liquefaction or shear failure during seismic events.

In addition to geological features, mechanical properties are essential. Before designing foundations for any structure, understanding them is mandatory for ensuring stability and safety. To do so, geotechnical subsurface measurements are conducted. They provide invaluable insights into the ground's behavior under load, enabling engineers to design foundations that are efficient, reliable and respecting the Eurocode standards.

Understanding the construction of 3D geological or geotechnical models is crucial for students. Constructing such models involves more than simply collecting data. It requires the ability to manage uncertainty, recognize and understand the various types of data, process various signals, and integrate diverse information sources. Borehole or punctual in-situ measurements provide detailed data, but they might not reflect broader regional trends. Conversely, and for example, electrical resistivity data offer a more extensive view of subsurface structures, but they are not as precise as point-based measurements. Training students to correlate and synthesize data of different types, resolutions and scales is essential to develop robust, reliable 3D models.

PEGGHy enables the deployment of standard (for pedagogical purposes) or more advanced (for innovative developments) geotechnical and geophysical instruments. Because it is a controlled geological environment, the features and models derived from the data can be quantitatively compared to the true underground, namely the digital twin of the platform. From a pedagogical point of view, this is extremely valuable, as it allows teachers to clearly point out limitations, uncertainties and pitfalls associated to geotechnical and geophysical characterization methods. In the following, we provide some examples of possible practical trainings and quantitative analysis of data enabled by PEGGHy.

5.1 Geotechnical in-situ measurements

Two key geotechnical field measurements are introduced to students to assess subsurface conditions, providing a solid background for understanding soil mechanical behavior and minimizing uncertainties related to composition, density, shear strength, and bearing capacity. These measurements help determine how the soil will respond to the weight of the structure and whether it has the necessary strength to support it without excessive settlement or failure.

Dynamic plate load test (PDL)

The lightweight deflectometer (*Plaque dynamique légère* -PDL- by Sol-Solution) is a field test designed to determine the dynamic deformation modulus (Evd) of subsoils, assess compaction quality and evaluate soil bearing capacity. Figure 3a presents a schematic of the device. Various empirical correlations (Prakashkumar & Rakesh, 2019) allow for the estimation of the static reloading deformation modulus (EV2) and the California Bearing Ratio (CBR).

Dynamic penetrometer test (Panda)

The lightweight variable energy version (Panda® by Sol-Solution) of the dynamic penetrometer test (DPT) is a portable device able to investigate the soil cone resistance down to a depth of 6 m. It is widely applied in France and other European countries, particularly for compaction control. The dynamic

penetrometer log data can be used to estimate several geotechnical parameters, including: the California Bearing Ratio (CBR), the static reloading deformation modulus (EV2), the Standard Penetration Test N60, the static cone resistance Q_c , the pressuremeter's limit pressure and modulus (p_l and EM). This is possible using direct correlation equations (Benz-Navarrete et al., 2020). Figure 3b presents a schematic representation of the device.

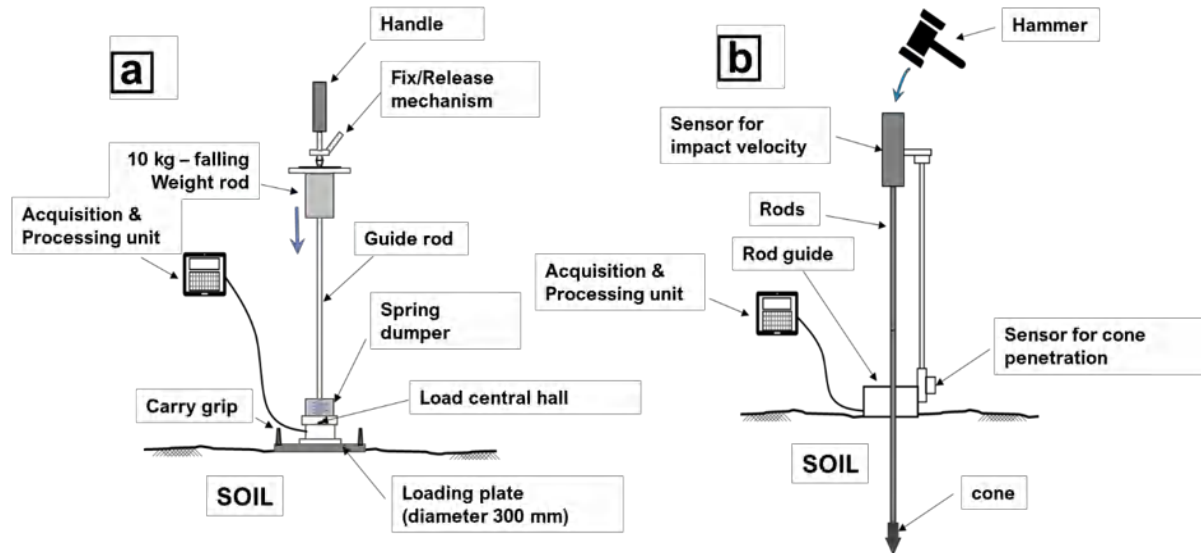


Figure 3. a) Lightweight deflectometer for the dynamic plate load test. b) Weight dynamic cone penetrometer.

Prospective learning activities in geotechnical engineering

As part of practical coursework in geotechnical engineering, students will be required to design an investigation program to establish a geotechnical model of the platform. They will define and conduct the necessary number of tests using both the Panda® and PDL devices. Additionally, complementary electrical and geomagnetic geophysical testing methods can be incorporated to verify the soil layers' continuity between tests locations and potentially identify subsurface anomalies.

Beyond its application in practical classes to demonstrate two widely known geotechnical in situ tests, advanced project-based learning activities are also planned. The intended learning outcome is to enhance students' ability to integrate local data—such as surface soil deformability from PDL and depth-dependent tip resistance from Panda tests—with the global inversion of geophysical surveys, to build the most accurate possible geotechnical design model.

Future developments could include scaled-down experimental devices for load testing of foundations elements (footing and pile), providing students with hands-on experience in geotechnical engineering.

5.2 Geophysical surveys

In geotechnical engineering, the use of geophysical methods is essential in supplementing traditional techniques by providing valuable data on subsurface conditions. Various geotechnical applications can be directly linked or compared with geophysical methods, each offering distinct advantages and working together to enhance site investigations.

While geotechnical methods deliver precise, direct, and reliable data on subsurface conditions, geophysical methods provide additional insights that contribute to a more thorough understanding of the site. As non-invasive techniques capable of covering larger areas more efficiently, geophysics is increasingly used alongside traditional geotechnical investigations to enhance site characterization, optimize foundation design, and ensure the safety and performance of engineering projects. By combining both approaches, engineers can minimize uncertainties, improve cost-efficiency, and make better-informed decisions throughout the design and construction processes.

Ground penetrating radar

Ground penetrating radar (GPR) is a non-invasive geophysical technique that uses high-frequency electromagnetic waves to investigate subsurface conditions. It provides a detailed view of the subsurface by detecting changes in the electrical properties (e.g., dielectric permittivity) of the underground materials. GPR is widely used for geotechnical investigations, archaeological surveys, environmental assessments, and other applications that require mapping near-surface features (e.g., Grandjean et al., 2000).

GPR can be easily implemented on top of PEGGHy. Figure 4 and 5 show a 600 MHz radargram obtained by ENSG students after basic processings such as redatuming, direct wave removal and gain application. The endpoints of the radargram are referenced in the RGF93 coordinate system so that the image can be introduced into the PEGGHy digital twin.

Figure 4 shows the western part of the digital twin, i.e., the base of the platform (pink) and the limit between the retention basin and the PEGGHy layers (green). In the radargram, a clear horizontal reflector is observed in the retention basin. Because water is accumulating in the basin thanks to the underlying impermeable geomembrane, this reflector can be interpreted as the water table. This illustrates the ability of GPR to image such a feature and to be used for mapping groundwater resources. The radargram also shows a dipping reflector, which corresponds to the limit between the retention basin and the PEGGHy layers. This reflector does not fit the true interface: it has an apparent dip, smaller than the true dip. This illustrates how radar sections can misposition and deform non-horizontal structures, similarly to post-stack sections in seismic reflection (e.g., Claerbout, 1985). When a wave velocity model is available, migrating these data allows to move reflectors to more accurate positions.

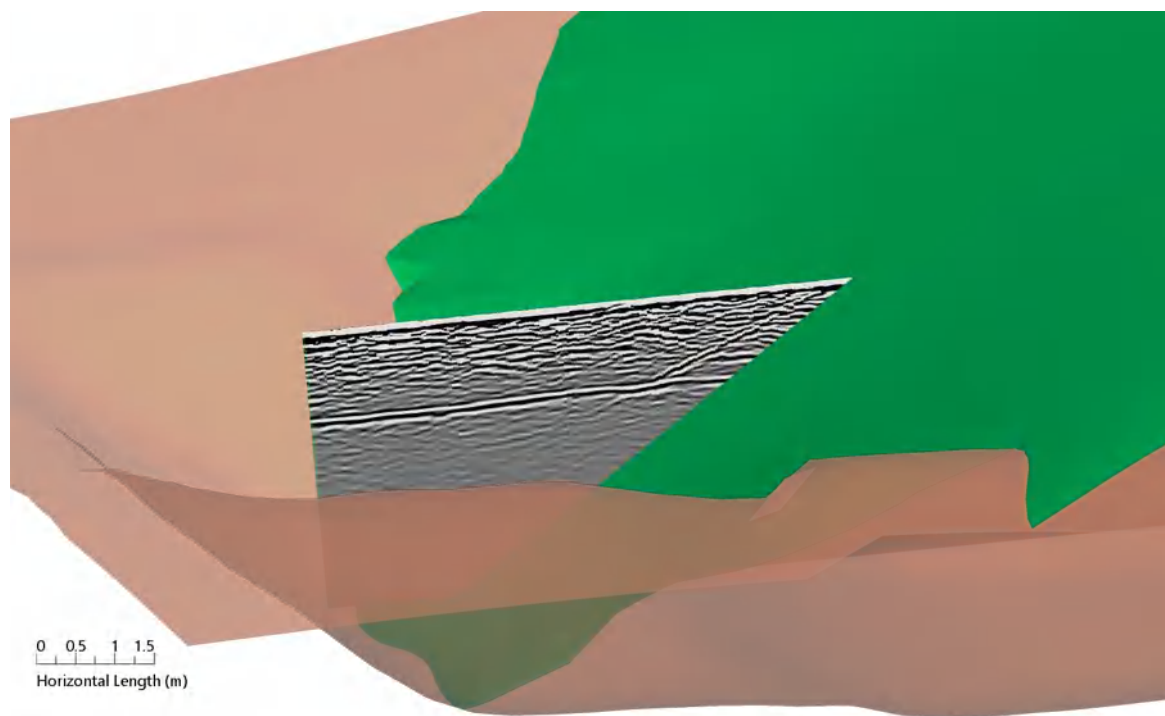


Figure 4. A GPR section in the western part of PEGGHy. The base of the platform is shown in pink and the limit between the retention basin and the PEGGHy layers is shown in green.

Figure 5 shows the same radargram as the one in Figure 4. The region of interest now is the other side of the limit between the retention basin and the layers. The horizon displayed in the figure is the top of the alluvial siliceous sands. This horizon is visible in the radargram, but it is shifted up and down by a couple of decimeters from the true horizon. Such a shift is due to the approximate surface topography of the radargram: instead of detailed 2D topographic data, a simple linear regression between the two endpoints of the radargram was used. As a consequence, the surface topography, even slight, maps into the horizons at depth. The effect is significant here because the shallowest, vegetal soil layer is very slow. When moving westward to the alluvial siliceous pebbles of the retention basin, the radar wave velocity suddenly increases, which pushes up the horizons in the radargram. These observations

illustrate how radar wave velocity impacts the obtained GPR images. Instead of a homogenous velocity for converting time-to-depth, as used in our example (0.1 m/ns), a heterogeneous velocity model should be implemented to accurately image and position the horizons.

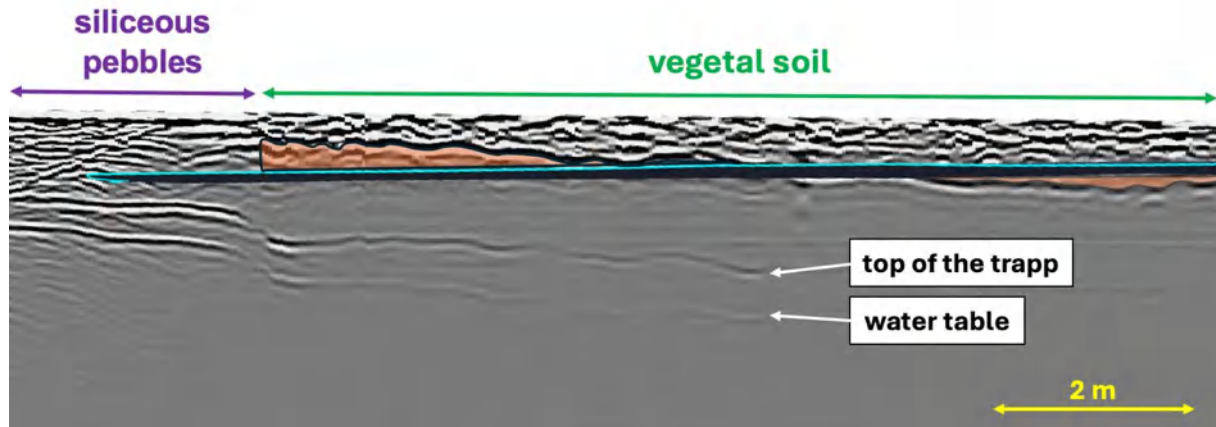


Figure 5. Same GPR section as in Figure 4, focused on the central part of the platform. The horizontal interfaces appear as highly deformed because of i) the approximated (i.e., flat) surface topography of the radargram and ii) the strong lateral velocity change when moving from the slow vegetal soil to the faster siliceous pebbles of the retention basin. To highlight the effect of the approximated topography, the shift between the top of the siliceous sands (whose borders are in cyan) and its corresponding reflector in the radargram is shown in shaded orange.

Electrical resistivity tomography

Electrical resistivity tomography (ERT) consists in measuring apparent resistivity data and inverting them to obtain the “true” resistivity values of the underground. This parameter refers to the property of a material to resist to the flow of an electrical current. In rocks, this parameter varies according to mineral composition, fluid content, porosity, fracture shapes, etc. Therefore, ERT is used for the identification of geological anomalies such as faults or cavities, mapping groundwater resources and locating contamination, and assessing soil properties for foundation design and geotechnical monitoring (e.g., Samouëlian et al., 2005; Cosenza et al., 2006).

Thanks to the vegetal soil layer, electrical resistivity surveys are easy to conduct on PEGGHy. Figure 6 shows both the apparent resistivity data acquired by ENSG students using a 48 electrode Wenner-Schlumberger array and the inversion result obtained using ResIPy (Blanchy et al., 2020). In addition to illustrating gradient descent optimization algorithms for deterministic inversion, such a field and processing work allows students to put in evidence the limited resolution of ERT by comparing the final geoelectrical image with the true underground (Figure 6). ResIPy, like any other ERT software, indeed provides a smooth image of the subsurface because of the incomplete and inaccurate data sampling (the inter-electrode distance is 1 m here) and because it applies model regularization to mitigate the non-uniqueness of the inverse problem (e.g., Friedel, 2003). Nevertheless, some structures can be recognized, such as the central fault between the two main compartments, the conductive vegetal soil layer on top more resistive materials in the western compartment, and the shape of the clay unit (including the vertical contact with the siliceous sands) in the eastern compartment. Deeper in the image, the resistivity values increase, which suggests that trapp and carbonate rocks are more resistive than sands. However, resistivity contrasts are weak there, because of i) possible weak contrasts between the involved layers and ii) the poor sensitivity at depth of the method.

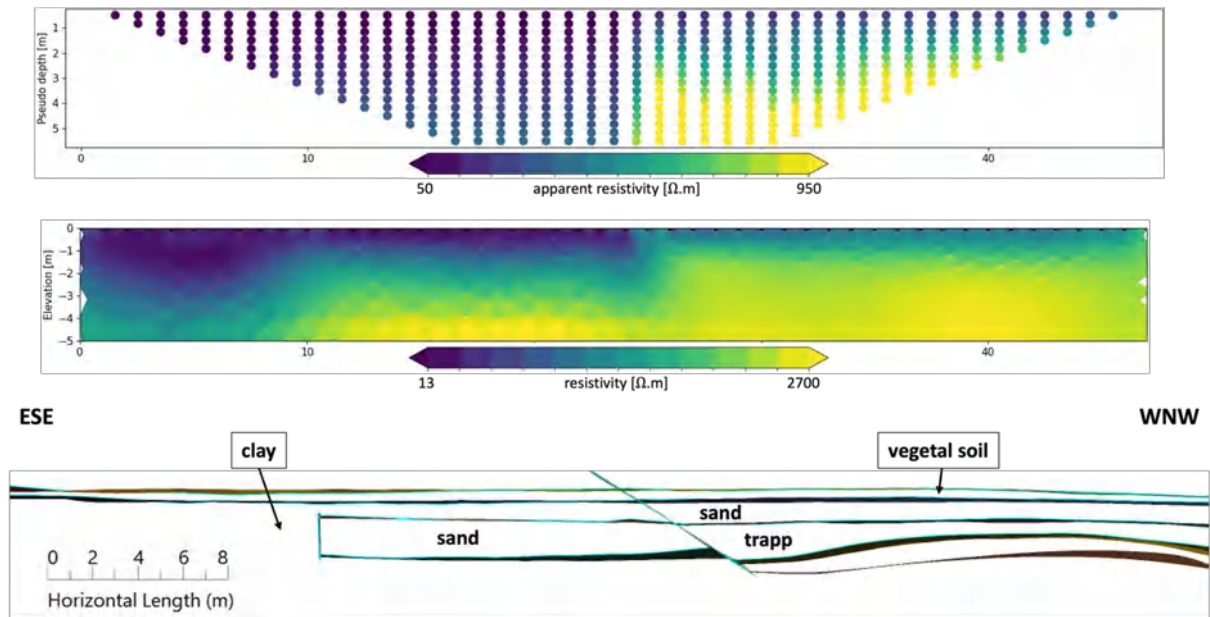


Figure 6. Top: apparent resistivity data from a Wenner-Schlumberger survey (48 electrodes, 1 m between two adjacent electrodes). Middle: geoelectrical section obtained from the inversion of the data. Bottom: section across the PEGGHy digital twin (for clarity, the base of the platform is not displayed).

Seismic refraction

Seismic methods rely on elastic waves propagating in the earth for imaging it at different scales. Among these methods, the seismic refraction approach is extensively used to study the near-surface. It relies on head waves, which travel along sub-horizontal interfaces and are easy to detect in seismic records because they arrive first. In geotechnical engineering, seismic refraction can be used to estimate the depth of the soil-bedrock interface (e.g., Abdelgowad et al., 2025) or geotechnical parameters like internal friction angle and Poisson's ratios (e.g., Pegah & Liu, 2016).

In summer 2024, ENSG students carried out a couple of three shotpoint seismic refraction profiles on top of PEGGHy. When inverting the data, both two-layer and three-layer models were tested, giving similar results for the depth of the shallowest discontinuity. Figure 7 shows the three-layer model obtained from a single profile. Comparing this model to the digital twin, one can interpret the shallowest discontinuity as the base of PEGGHy, meaning that all the inner layers of the platform are homogenized by the seismic method implemented here. Moreover, the investigation of the discrepancy between the true base and the one derived from all the seismic profiles in the ESE half of the platform reveals a Gaussian posterior uncertainty $\sigma = 22$ cm. This estimate is an interesting pedagogical input, as it points out the typical amount of layer thickness uncertainty in seismic refraction characterization of the near-surface. Furthermore, such a value allows us interpreting the WNW part of the discontinuity as the folded interface between the siliceous sands and the underlying crushed carbonate rocks.

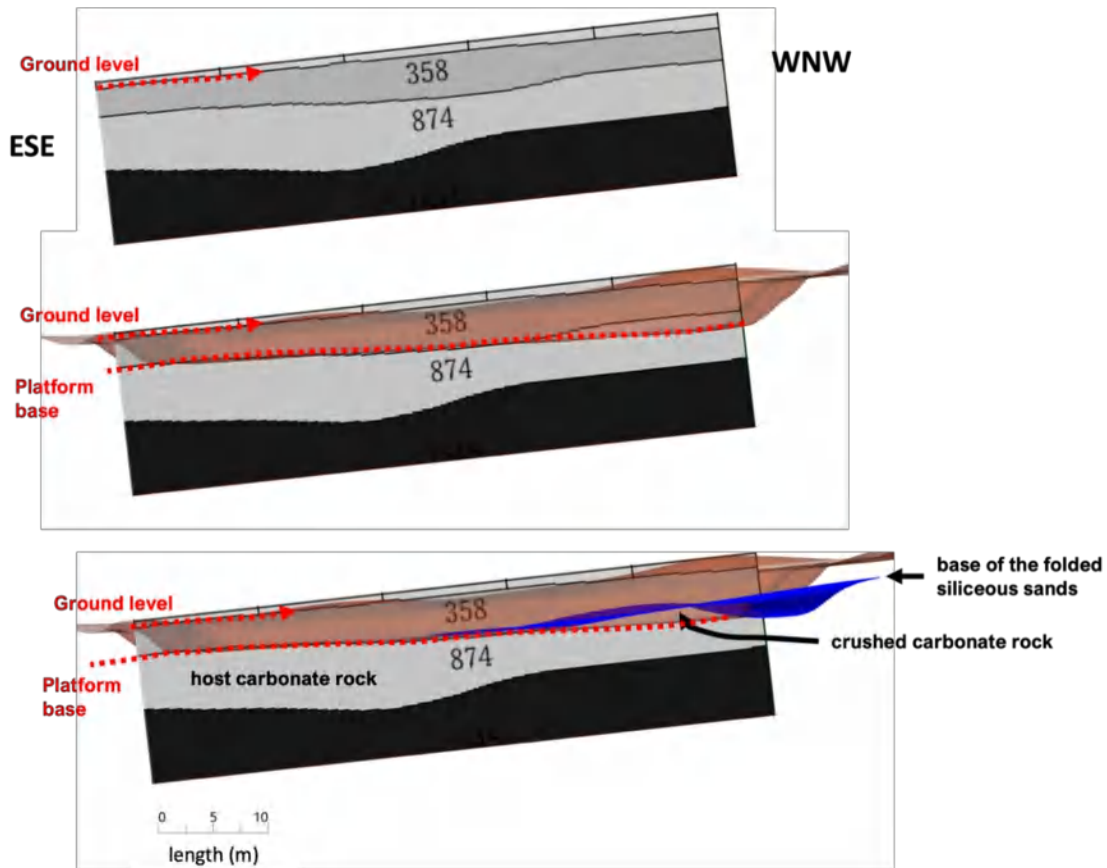


Figure 7. Result of a 2D seismic refraction tomography in PEGGHy. The obtained model shows three layers with different P-wave velocities. Comparing it to the digital twin, the shallowest discontinuity of the model is interpreted as the interface which separates the artificial units of the platform, especially the folded siliceous sands, from the underlying carbonate rocks.

6 Conclusion

PEGGHy enables enhancements of geo-engineering studies by providing near-real-scale practical experiences to students, allowing them to follow the full cycle of subsurface data acquisition and analysis using measurements from geotechnical and geophysical instruments. Each method can be taught independently, as presented in this paper, or it can be considered with other methods to build geological or geotechnical models from the integration of various data.

Because PEGGHy is a controlled geological environment, the features and models derived from the data can be quantitatively compared to the true underground, namely the 3D digital twin of the platform. From a pedagogical point of view, this is extremely valuable, as it allows teachers to clearly point out the inherent limitations (resolution, depth of investigation), uncertainties and pitfalls associated with all the geophysical and geotechnical characterization methods. Furthermore, the digital twin allows running numerical simulation codes and comparing their results to real data. This offers a unique opportunity to teach and test numerical schemes, discretization algorithms and monitoring methods.

Beyond the acquisition and data analysis examples presented in this paper, many other pedagogical uses can be considered, involving other processings (e.g., radargram migration, constrained inversions), settings (e.g., dipole-dipole ERT, lower frequency GPR) or methods (MASW, induced polarization, electromagnetic surveys, etc.). In addition, wellbores within the platform will open pedagogical applications in hydrogeology in the future.

PEGGHy is available to any academic training, research or development projects which require equipment or method testing based on the comparison of experimental measurements with features from the digital twin. The access to the platform and related data can be obtained by contacting the Graduate School of Geological Engineering or the authors.

Acknowledgements

The design of the platform was carried out by the ENSG teaching team, followed by technical drawings from the “Concept Infra” company. The contract was awarded to the “Xardel Démolition” company. The platform is equipped with optical fibers provided by our partners ANDRA and SERCEL (VIRIDIEN). Photogrammetric levées of the platform were performed by ENEREX SAS. Special acknowledgment is due to Anthony Yorillo having initiated the preliminary work on the raw data underlying the digital twin.

References

- Abdelgowad, A.M., El-Haddad, A.E., Aglan, M.I., Hamed, A. (2025). Seismic refraction investigation of the shallow bedrock in New Qena City, Eastern Desert, Egypt. *Scientific Reports*, 15, 2646.
- Ajo-Franklin, J.B., Dou, S., Lindsey, N.J., Monga, I., Tracy, C., Robertson, M., Rodriguez Tribaldos, V., Ulrich, C., Freifeld, B., Daley, T., Li, X. (2019). Distributed acoustic sensing using dark fiber for near-surface characterization and broadband seismic event detection. *Scientific Reports*, 9(1), pp. 1-14.
- Benz-Navarrete, M.A., Breul, P., Bacconet, C., Moustan, P. (2020). The Panda®, variable energy lightweight dynamic cone penetrometer: a quick state of art. *Engineering Geology*.
- Blanchy, G., Saneiyan, S., Boyd, J., McLachlan, P., Binley, A. (2020). ResIPy, an intuitive open-source software for complex geoelectrical inversion/modelling. *Computers & Geosciences*, 137, 104423.
- Caumon, G., Collon, P., Le Carlier de Veslud, C., Viseur, S., Sausse, J. (2009). Surface based 3D modeling of geological structures. *Mathematical Geosciences*, 41, pp. 927-945.
- Claerbout J.F. (1985). *Imaging the earth's interior*, Blackwell Scientific Publications, Oxford.
- Cosenza, P., Marmet, E., Rejiba, F., Cui, Y.J., Tabbagh, A., Charlery, Y. (2006). Correlations between geotechnical and electrical data: a case study at Garchy in France. *Journal of Applied Geophysics*, 60, pp. 165-178.
- Dou, S., Lindsey, N., Wagner, A.M., Daley, T.M., Freifeld, B., Robertson, M., Peterson, J., Ulrich, C., Martin, E.R., Ajo-Franklin, J.B. (2017). Distributed acoustic sensing for seismic monitoring of the near surface: a traffic-noise interferometry case study. *Scientific Reports*, 7(1), pp. 1-12.
- Friedel, S. (2003). Resolution, stability and efficiency of resistivity tomography estimated from a generalized inverse approach. *Geophysical Journal International*, 153(2), pp. 305-316.
- Grandjean, G., Gourry, J.C., Bitri, A. (2000). Evaluation of GPR techniques for civil-engineering applications: study on a test site. *Journal of Applied Geophysics*, 45, pp. 141-156.
- Mallet, J.L. (1992). Discrete smooth interpolation in geometric modelling. *Computer Aided Design*, 24, pp. 178-191.
- Nziengui-Bâ, D., Coutant, O., Moreau, L., Boué, P. (2023). Measuring the thickness and Young's modulus of the ice pack with DAS, a test case on a frozen mountain lake. *Geophysical Journal International*, 233(2), pp. 1166-1177.
- Pegah, E., Liu, H. (2016). Application of near-surface seismic refraction tomography and multichannel analysis of surface waves for geotechnical site characterizations: a case study. *Engineering Geology*, 208, pp. 100-113.
- Prakashkumar, M., Rakesh, K. (2019). Correlative study of LWD, DCP and CBR for sub-grade. *Journal of Engineering Trends and Technology*, 67(9), pp. 2231-5381.
- Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., Richard, G. (2005). Electrical resistivity survey in soil science: a review. *Soil & Tillage Research*, 83, pp. 173-193.
- Zhan, Z. (2020). Distributed acoustic sensing turns fiber-optic cables into sensitive seismic antennas. *Seismological Research Letters*, 91(1), pp. 1–15.

Authors' bios

Judith Sausse, Ecole Nationale Supérieure de Géologie, GeoRessources, Université de Lorraine (France)

Dr. Judith Sausse is a Professor at the Université de Lorraine within the GeoRessources Lab. She is currently serving as the Director of the National Graduate School of Geological Engineering (ENSG). She is a recognized expert in geosciences, specializing in reservoir geophysics, fractured reservoirs, geothermal exploration, and 3D geomodelling. Her research has led to 38 publications, and she is particularly noted for her contributions to geothermal energy systems, deep geothermal exploration, and petrophysics. Her teaching activities in geophysics cover gravimetric, magnetic, seismic, electrical, and electromagnetic methods, from both theoretical and applied perspectives. Her goal is to provide an in-depth understanding of these methods, focusing on subsurface techniques as well as the interpretation of well data in fractured reservoir domains. These courses are applied during field works at ENSG.

Paul Cupillard, Ecole Nationale Supérieure de Géologie, GeoRessources, Université de Lorraine (France)

Dr. Paul Cupillard is an Associate Professor at Université de Lorraine (UL) within the GeoRessources Laboratory. He obtained a M.Sc. in Geophysics from Strasbourg University (France) and a Ph.D. in Seismology from the Institut de Physique du Globe de Paris (IPGP, France). In 2008, he flew to California to work as a post-doc in the Berkeley Seismological Laboratory, UC Berkeley, for 30 months. After a second post-doc at IPGP, he obtained his current position at UL. A large part of his research is carried out in the frame of the RING-GoCAD consortium. His main research axes are i) the numerical simulation seismic wave propagation in complex geological media, ii) the homogenization of elastic properties for the seismic wave equation, iii) the inversion of seismic waveforms to retrieve geological parameters. On the teaching side, Dr. Cupillard give many classes at the National Graduate School of Geological Engineering, where he teaches the Finite Element method, Geomodelling, and Geophysics. In this last field, both theoretical and practical aspects are considered, including field works.

Adel Abdallah, Ecole Nationale Supérieure de Géologie, LEMTA, Université de Lorraine (France)

Dr. Adel Abdallah is an Associate Professor of Geotechnical Engineering at the National Graduate School of Geological Engineering, Université de Lorraine, France, since 2000. He holds a Civil Engineering BEng from ENI Gabès, Tunisia (1993), a MSc in Civil and Mining Engineering (1995), and a PhD in Geotechnical Engineering (1999) from Lorraine National Polytechnical Institute in Nancy, France. His research focuses on coupled THM behaviour of natural, compacted and treated soils. He is particularly interested in numerical modelling and model parameter calibration, and in applications of machine learning and artificial intelligence in Geotechnical Engineering. He teaches soils mechanics at graduate and undergraduate levels, numerical modelling, geotechnical design and machine learning. He served as the Academic Dean of ENSG from 2012 to 2018.

Yves Géraud, Ecole Nationale Supérieure de Géologie, GeoRessources, Université de Lorraine (France)

Dr. Yves Géraud is a Professor at Université de Lorraine, France. He obtained a PhD in geology and petrophysics from Université de Marseille in 1991 and then he worked as a research engineer at the applied geology laboratory of Université de Marseille. Between 1993 and 1995, he was Assistant Professor at ENS-Lyon. In 1995, he obtained an Assistant Professor permanent position at Université de Strasbourg. In 2012, he obtained his current position. He is the head of the teaching department « Géologie-Energies », a specialty of the National Graduate School of Geological Engineering devoted to the exploration of various energetic systems. His teachings are about structural geology, petrophysics, diagraphy, interpretation of geophysical data, field geology, energetic systems. He is also the head of the GreStock (for Reservoir geology and storage) team at GeoRessources Lab. It is a pluri-disciplinary team focuses on exploration of new energetic resources. His activity focuses on structural geology, petrophysics. He led several national and international research programs that yields 120 publications.

Marc Diraison, Ecole et Observatoire des Sciences de la Terre, Université de Strasbourg, GeoRessources, Université de Lorraine (France)

Dr. Marc Diraison is an Associate Professor at Université de Strasbourg since 2000. His current research activity takes place within the GeoRessources Laboratory and his interests focus on structural geology, seismic interpretation and tectonics. His main research axes are i) relationships between tectonics and sedimentation and ii) fractured reservoirs within basins and basement for fluid circulation and geothermal exploration. In addition to classes, his teaching activity is oriented towards field schools at Université de Strasbourg and at the National Graduate School of Geological Engineering in Nancy.

Constantin Oltéan, Ecole Nationale Supérieure de Géologie, GeoRessources, Université de Lorraine (France)

Dr. Constantin Oltéan is an Associate Professor at the University of Lorraine. His teaching activities are mainly carried out at the Ecole Nationale Supérieure de Géologie of Nancy. They focus on engineering sciences and their applications in the geosciences (fluid mechanics, hydraulics, hydrogeology, modeling the behavior of aquifers, geothermal energy). As for his research activities, they are developed at the Georessources laboratory and focus particularly on: (i) the transfer of miscible fluids in porous media, taking into account phase heterogeneities and (ii) the physico-chemical interactions between the porous matrix and the liquid phase as part of a dissolution/precipitation reaction. In recent years, he has also focused on instabilities generated by non-Newtonian fluids in the presence or absence of surfactants and on flow in rough fractures. Whatever the topic, all his work is based on a strategy that integrates a triple approach, i.e. experimental, numerical and theoretical.

Fabrice Golfier, Ecole Nationale Supérieure de Géologie, GeoRessources, Université de Lorraine (France)

Dr. Fabrice Golfier is a Professor at the National Graduate School of Geological Engineering, Université de Lorraine, France, where he teaches environmental engineering and hydrogeology courses. His research interests at the GeoRessources Laboratory focuses on coupled processes in porous media, including i) theoretical and numerical contributions to multi-scale modeling and ii) targeted applications in geosciences related with a sustainable use of subsurface resources (mineral deposit formation, hydrogen storage, nuclear waste deposit...) and environmental issues (groundwater contaminant transport, bioremediation of polluted sites).

Olivier Cuisinier, Ecole Nationale Supérieure de Géologie, LEMTA, Université de Lorraine (France)

Dr. Olivier Cuisinier is a Professor of Geotechnical Engineering at the National Graduate School of Geological Engineering, Université de Lorraine, France, since 2008. He earned his PhD from Université de Lorraine in 2002 before joining the Laboratoire Central des Ponts et Chaussées (LCPC) as a Researcher, where he worked until 2008. That year, he transitioned to academia as an Associate Professor at Université de Lorraine, and in 2020, he was promoted to Professor of Geotechnical Engineering. Dr. Cuisinier's research focuses on the fundamental behavior of soils and the advanced laboratory characterization of fine-grained soils. With nearly 20 years of experience in soil mechanics, his expertise covers unsaturated expansive soils, naturally and artificially cemented soils, with a particular emphasis on their long-term behavior.

Beyond his research, Dr. Cuisinier actively contributes to the geotechnical community. Since 2024, he has been serving as the Chair of the Scientific Committee of the French Association for Soil Mechanics and Geotechnical Engineering.

***Links to Research on Learning
and on Engineering Education***

Teaching soil mechanics core concepts: mapping the structure of university textbooks worldwide

M. Calvello

University of Salerno, Fisciano (SA), Italy
mcalvello@unisa.it

ABSTRACT: Textbooks serve as essential reference materials for educators, structured to introduce concepts in a logical sequence. This study explores how soil mechanics concepts are treated in university textbooks, by analysing the Table of Contents (TOCs) of introductory soil mechanics and geotechnical engineering books. The research begins with the compilation of a list of these textbooks—sourced from personal knowledge, colleague recommendations, and bibliographic reviews—followed by an initial discussion on terminology and the presentation of key features of: landmark textbooks, latest editions of widely adopted textbooks written in English, textbooks written in other languages. A comparative analysis of the considered textbooks is then conducted by considering the topics addressed and their sequence of presentation. The main outputs of the analysis revolve around the original definition and clustering of soil mechanics key topics and core concepts. The findings aim to inform educators about similarities and differences in topic coverage and sequencing within introductory soil mechanics and geotechnical engineering textbooks written across different time periods and languages.

Keywords: Textbooks, Soil mechanics, Comparative analysis

1 Introduction

Textbooks are, in many cases, the primary reference material in the educational framework of a university course. These books are authored by instructors who often have significant experience in teaching and research. The structure of textbooks is designed to introduce fundamental concepts in a logical sequence, beginning with foundational principles before advancing to more complex topics. The Table of Contents (TOC) of textbooks can thus be considered a sort of roadmap for teaching to students the main concepts of a course or discipline, as it implicitly highlights a set of concepts' categories and a defined sequence for teaching and learning them. Numerous textbooks are used throughout the world in core university courses in soil mechanics and geotechnical engineering. This study aims to explore how soil mechanics concepts are treated in these textbooks. This study will also provide a (relatively long) list of soil mechanics textbooks that, as a compiled and commented list of references, may be useful for geotechnical educators worldwide wishing to expand their teaching material.

2 Compiling the list of textbooks

The author has looked for books that can be considered introductory soil mechanics textbooks. The books of interest are the ones that have been used or could be used, in total or in a significant part, within undergraduate courses introducing soil mechanics topics to undergraduate civil engineering students for the first time. Therefore, books of interest include textbooks that discuss geotechnical engineering applications after an in-depth presentation of soil mechanics fundamental concepts, but do not include geotechnical engineering textbooks that assume that a thorough knowledge of soil mechanics fundamental concepts must be acquired using other reference material (e.g., books

organized in sequence). The adopted list of books has been compiled from different sources: personal knowledge, valuable recommendations from colleagues, and a bibliographic review.

Recommendations from colleagues were mainly used for discovering textbooks adopted where English is not the mother tongue and to get information on books written in English widely adopted globally. To this end, besides personal contacts with a few colleagues, an email survey was conducted involving the members of the ISSMGE Technical Committee 306 “Geo-engineering education”. Three questions were asked. What book do you, or your colleagues, use in your University to teach the first 'Soil mechanics' course? What are the books (or the book) most widely used in your country? Could you send me the links to TOCs of such books or a file with the TOCs? 22 useful replies were received and, interacting with the respondents, many relevant comments and TOCs were collected. For text and TOCs received in languages not spoken by the author, automatic translation tools were used to translate them into English. The survey carried out cannot be considered in any way comprehensive, as many languages (and countries) are missing from the list. Moreover, it must be noted that in some countries (e.g., Spain, Brazil) using lecture notes produced locally by University professors, instead of published books, is still a widespread practice. For such cases, the analysis of syllabi would be more appropriate to understand how soil mechanics and geotechnical engineering concepts are introduced to undergraduate students, yet this goes beyond the scope of this study. The search for books written in English was also conducted browsing the web, library catalogues and using these repositories: Perlego (<https://www.perlego.com/>), Google books (<https://books.google.com/>), the Internet Archive (<https://archive.org/>). The main keywords adopted were soil mechanics, geotechnical engineering and geotechnics.

3 Textbooks

3.1 Analysed textbooks and terminology

Tables 1 and 2 show an overview of the analysed textbooks, respectively for the 24 books written in English and for the 18 books written in languages other than English. The tables report the year of publication of the last edition of each textbook even when the tables of contents of previous editions may have been considered in this work. The ID includes the authors' initials and the year of publication, for the books not written in English two initial capital letters are also used.

Most of the 42 books analysed herein use the words “soil mechanics” (30 books) in their title, in a few cases together with the words “foundations” (*Bu2011*, *So1979*, *CR-N1981*, *SP-M2007*) or “applications” (*Po2014*). 11 books adopt the words “geotechnics” or “geotechnical engineering”, and the remaining book is called *Fundamentals of ground engineering* (*At2014*). One may expect that the different titles may also give an indication on how much the textbook is devoted to introducing, essentially, the fundamental concepts of soil mechanics or, alternatively, to give significant space to geotechnical applications. Such a correlation is lacking or not evident. For instance, very popular English books like *Smith's elements of soil mechanics* (*Sm2021*) or *Craig's soil mechanics* (*KC2019*), whose latest editions are the 10th and the 9th respectively, devote a large numbers of chapters to geotechnical applications while, at the other end of the spectrum, the two Italian books called *Geotechnics* (*IT-L2012*) and *Principles of geotechnics* (*IT-B2021*) and the French book *Theory and practice of geotechnics* (*FR-P2013*) only devote the last two final chapters to applications.

It is worth noting that Atkinson promotes the use of the phrase “ground engineering” encompassing both soil mechanics and geotechnical engineering, which have therefore, in this case, a clearly different and complementary meaning. Indeed, in his book *Fundamentals of ground engineering* (*At2014*) the chapters are grouped in four sections: i) discovering the ground; ii) essential physics and mechanics; iii) soil mechanics; iv) geotechnical engineering. Often used in the titles, to highlight the fact that these textbooks are introductory books for the subject, are the words “fundamentals” (5 times), “principles” (5 times), “elements” (3 times), “introduction to” (3 times) and “basic” (3 times). These words are essentially used as synonyms, as no distinct meanings have been identified. No clear trends have emerged regarding the authors' country of origin, the language used, or the year of publication. In essence, all the terminology choices made by the authors of the analysed textbooks appear to be driven by individual preferences.

Table 1. Analysed textbooks written in English

ID	Authors	Ed*	Year	Title
AB1978	Atkinson, Bransby	1	1978	The mechanics of soils: an introduction to critical state soil mechanics
At2007	Atkinson	2	2007	The mechanics of soils and foundations
At2014	Atkinson	1	2014	Fundamentals of ground engineering
Ba2016	Barnes	4	2016	Soil mechanics: principles and practice
Br2023	Briaud	2	2023	Geotechnical engineering: unsaturated and saturated soils
Bu2011	Budhu	3	2011	Soil mechanics and foundations
Bu2015	Budhu	1	2015	Soil mechanics fundamentals
CYK2010	Coduto, Yeung, Kitch	2	2010	Geotechnical engineering: principles & practices
Da1979	Das	1	1979	Introduction to soil mechanics
Da2021	Das	10	2021	Principles of geotechnical engineering
DS2016	Das, Sivakugan	5	2016	Fundamentals of geotechnical engineering
HKS2023	Holtz, Kovacs, Sheahan	3	2023	An introduction to geotechnical engineering
KC2019	Knappet, Craig	9	2019	Craig's soil mechanics
La2008	Lancellotta	2	2008	Geotechnical engineering
LW1969	Lambe, Withman	1	1969	Soil mechanics
Mu2009	Muir Wood	1	2009	Soil mechanics: a one-dimensional introduction
No2013	Nova	1	2013	Soil mechanics
Or1995	Ortigao	1	1995	Soil mechanics in the light of critical state theories
Po2014	Powrie	3	2014	Soil mechanics: concepts and applications
Sm2021	Smith	10	2021	Smith's elements of soil mechanics
So1979	Sowers	4	1979	Introductory soil mechanics and foundations
Ta1948	Taylor	1	1948	Fundamentals of soil mechanics
TPM1996	Terzaghi, Peck, Mesri	3	1996	Soil mechanics in engineering practice
We2009	Wesley	1	2009	Fundamentals of soil mechanics for sedimentary and residual soils

* Last published edition (hyperlink to main web reference, i.e., editor's page when available)

Table 2. Analysed textbooks written in languages other than English

ID	Authors	Ed*	Year	Language	Title (English translation)
AR-A2019	Al-Qasabi	1	2019	Arabic	Soil mechanics
CH-G2022	Li, Zhang, Yu	3	2022	Chinese	Soil mechanics
CH-L2020	Liu	5	2020	Chinese	Soil mechanics
CR-N1981	Nonveiller	1	1981	Croatian	Soil mechanics and foundation
DA-O2012	Ovesen	2	2012	Danish	Textbook in geotechnics
FR-P2013	Plumelle et al.	1	2013	French	Theory and practice of geotechnics
FR-S1997	Schlosser	2	1997	French	Elements of soil mechanics
GR-K2016	Kavvas	2	2016	Greek	Elements of soil mechanics
IT-B2021	Berardi	4	2021	Italian	Principles of geotechnics
IT-B2018	Burghignoli	1	2018	Italian	Soil mechanics
IT-C2004	Colombo, Colleselli	3	2004	Italian	Elements of geotechnics
IT-L2012	Lancellotta	4	2012	Italian	Geotechnics
KO-L2021	Lee	3	2021	Korean	Principles of soil mechanics
PO-D2006	De Sousa Pinto	3	2006	Portuguese	Basic soil mechanics course
PO-M2024	Matos Fernandes	6	2024	Portuguese	Soil mechanics: concepts and basic principles
SP-M2007	Muzas Labad	1	2007	Spanish	Soil mechanics and foundations
TU-K1999	Kumbasar, Kip	1	1999	Turkish	Soil mechanics problems
TU-U2020	Uzuner	11	2020	Turkish	Basic soil mechanics with solved problems

* Last published edition (hyperlink to web reference in original language, when available)

3.2 Landmark textbooks written in English

One of the first published textbooks is *Soil mechanics in engineering practice* by K. Terzaghi and R.B. Peck (1948). The 3rd and last edition (with co-author G. Mesri) dates 1996. The book is structured in three parts: A) Physical properties of soils, B) Theoretical soil mechanics, and C) Problems of design and construction. The structure of this book is clearly tied with an instructional purpose, expressed in the preface of the first edition as follows: *'[the first] two parts are very short, but they contain all that engineering students and the average engineer need to know about soil mechanics proper at the present time. The heart of the book is Part C. Part C deals with the art of getting satisfactory results in earthwork and foundation engineering at a reasonable cost, in spite of the complexity of the structure of natural soil strata and in spite of the inevitable gaps in our knowledge of the soil conditions.'* They continue by saying *'Therefore, the experienced engineer is advised to start reading the book at the beginning of this part. He should use Parts A and B only for reference, to get information about concepts with which he is not yet familiar.'* The text highlights two categories of envisioned readerships: (university) students and practising geotechnical engineers. Considering that from the first to the last edition almost 50 years elapsed, it is worth to highlight that the structure of the book has not changed and to report text written in 1996 by the (living) authors (i.e., Peck and Mesri): *'In the half-century since these words were written, research [...] has continued unabated [...] [part A] of this edition is essentially a digest of the findings of research workers concerning the properties of soil that are of interest to engineers. The digest presents the findings from a fundamental point of view rather than as representing any one school of thought. [...] on the other hand [part B] has been increased only slightly, because the essential theoretical tools were already available 50 years ago.'*

Not too different is the structure of the other “grandfather” of geotechnical engineering textbooks, *Fundamentals of soil mechanics* by D.W. Taylor (1948), who writes: *'Books of a number of types on this subject are needed [...] This book is written as a textbook for use in graduate courses, but it is presented in such form that by the omission of certain portions it can be used in undergraduate courses. Practising engineers and specialists in soil engineering may find the book of interest and value but, primarily, it is written for the student.'* The topics deemed fundamental for soil mechanics are presented by means of 20 chapters. Although the book does not explicitly assign the chapters to parts or sections, the following thematic grouping can be inferred: origin, physical properties and classification of soils; soil investigation; role of water in soils; consolidation; stresses and soil settlements; soil strength; geotechnical applications.

Very different is the structure of another “milestone textbook”: *Soil mechanics* by T.W. Lambe and R.V. Whitman (1969), 10 years later also published in a SI edition. The preface of this book starts with the following almost-tautological statement: *'Soil mechanics is designed as a text for an introductory course in soil mechanics.'* Yet, the subsequent text masterfully states, in just one sentence, the gist of the textbook and its instructional purpose: *'An intense effort was made to identify the truly fundamental and relevant principles of soil mechanics and to present them clearly and thoroughly.'* This book has 34 chapters structured in five parts: I) Introduction; II) The nature of soil; III) Dry soil; IV) Soil with water – no flow or steady flow; V) Soil with water – transient flow. The key driver of the explanations is clearly the state of the soil in relation the absence or presence of water filling the void space. Concerning the main soil mechanics concepts addressed, the sequence of presentation in the three parts follows a similar structure. At first, stresses are presented: in the dry soil mass, introducing the principle of effective stress, and considering undrained loading and consolidation. Then, stress-strain relationships are discussed, in general and in relation to drained and undrained conditions. In each part, a chapter is also specifically devoted to shear strength considering: cohesionless soils, drained and undrained conditions. In part IV, seepage is also addressed.

Finally, a singular book worth mentioning in this section, even if it cannot be considered a textbook for introductory soil mechanics courses (and thus it was not included in Table 1), is *Fundamentals of soil behavior* (Mitchell and Soga, 2005), whose first edition was written by J.K. Mitchell in 1976 and was published in the same book series of Soil Mechanics (Lambe and Whitman, 1969). The book is herein cited because it can be considered, in my opinion, a key reference for all geotechnical instructors looking for teaching material aimed at developing *'an understanding of the factors determining and controlling the engineering properties of soils, with emphasis on the why aspect of soil behavior.'* To this aim, in the book, *'principles from chemistry, geology, material science and physics are introduced as necessary to develop background of the phenomena under study.'*

3.3 Widely-adopted recent textbooks written in English

The books written in English whose latest edition has been published from 2010 onwards are 13. Albeit the survey carried out cannot be considered exhaustive, and thus the information acquired is not statistically significant, the following two books have been frequently mentioned: *Craig's soil mechanics*, by J.K. Knappet and R.F. Craig (KC2020), and *Principles of geotechnical engineering*, by B.M. Das (Da2021). They are also among the books counting more published editions, respectively 9 and 10, which is a factor that can be considered a proxy for the diffusion of a textbook.

Craig's soil mechanics (9th ed., 2020) is a textbook that 'covers fundamental soil mechanics and its application in applied geotechnical engineering from A to Z and at the right depth for an undergraduate civil engineer, with sufficient extension material for supporting MSc level courses, and with practical examples and digital tools to make it a useful reference work for practising engineers.' This textbook is explicitly composed of a 7-chapter part I 'Development of a mechanical model for soil' and a 6-chapter part II 'Applications in geotechnical engineering'. The book also features a companion website (<https://routledgetextbooks.com/textbooks/9781138070066/>), with additional teaching and learning resources, tailored to both students and educators. *Principles of geotechnical engineering* (10th ed., 2022) is marketed as an 'introduction to geotechnical engineering [...] ideal for the introductory course taken by most civil engineering students [...] [providing an] overview of soil properties and mechanics together with coverage of today's field practices and basic engineering procedures [...] [and] the background students need for advanced design-oriented courses as well as professional practice.' The book comprises 19 chapters almost evenly balanced, in numerical terms, among introduction and basic characteristics of soils, fundamental soil mechanics topics, and geotechnical applications. Similarly to KC2020, also this textbook has online supplements. For students they are provided in a platform called WebAssign, in the form of questions, videos and tutorials, feedback on coursework and progress monitoring tools. For the instructors there is a Companion Site (<https://companion-sites.cengage.com/>) as well a learning platform called MindTap featuring dynamic applications and real-time course analytics.

3.4 Textbooks written in other languages

The non-English textbooks considered in this study are 18. They are written in 11 different languages (Table 2). Most of them had their last edition published less than 20 years ago (exceptions: , CR-N1981, FR-S1997, TU-K1999, IT-C2004), some of them are very recent (CH-L2020, TU-U2020, IT-B2021, KO-L2021, CH-G2022, PO-M2024), and in a couple of cases it was not possible to retrieve the date of publication (AR-A2019, CH-S). In terms of editions, the textbooks featuring more than three editions are in Chinese (CH-L2020), Italian (IT-L2012, IT-B2021), Portuguese (PO-M2024) and Turkish (TU-U2020).

No regional or national trends emerge from this sample of textbooks. However, a few comments on what is (or is not) addressed in these books can be made.

- The way books introduce the reader to the subject varies widely, both in terms of number of chapters devoted to this initial part and in how the initial description, characterization and classification of soils is presented (this is also true for textbooks written in English).
- Chapters specifically devoted to continuum mechanics concepts, as a way of introducing stresses and strains in soils, are present only in books written in a few languages: three books written in Italian (IT-B2018, IT-C2004, IT-L2012), the two French books (FR-P2013, FR-S1997), and the books written in Croatian (CR-N1981), Danish (DA-O2012) and Greek (GR-K2016).
- Books devoting one chapter specifically to soil water and to the concept of effective stress are a minority (IT-B2021, IT-C2004, IT-L2012, KO-L2021, PO-D2006, TU-U2020).
- All books devote at least one chapter to groundwater flow.
- All books devote at least one chapter to volumetric compressibility and/or consolidation.
- Almost all books devote one or more chapters to shear strength, with the notable exception of some French (FR-P2013) and Italian (IT-B2018, IT-L2012) textbooks, wherein this concept is addressed within wide-ranging chapters dealing with constitutive modelling.
- Chapters devoted to soil exploration or soil testing are present only in books written in a few languages: Italian (4 books), French (2 books), Greek, Croatian and Spanish (1 book each). Soil investigation is introduced in specific chapters in three books (FR-P2013, IT-C2004, SP-M2007), mechanical laboratory tests are addressed in 4 books (GR-K2016, IT-B2018, IT-B2021), and in-situ tests in 5 books (CR-N1981, FR-S1997, IT-B2018, IT-C2004, IT-L2012).

4 Topics addressed and sequence

4.1 Books' chapters and grouping of topics

To discuss the topics addressed in the analysed textbooks, it may be useful to group them in classes: i) introduction and basic characteristics of soils, ii) soil investigation and testing, iii) soil mechanics core concepts, iv) geotechnical applications. This grouping is evidently influenced by the many TOCs considered in this study but remains subjective. In fact, some books are explicitly structured in parts or sections that collect their chapters (e.g., *TPM1996* part A: Physical properties of soils, part B: Theoretical soil mechanics, part C: Problems of design and construction; *At2014*: Discovering the ground, Essential physics and mechanics, Soil mechanics, Geotechnical engineering; *KC2020* part I: Development of a mechanical model for soil, part II: Applications in geotechnical engineering), yet the majority of them only uses the chapters as the highest category of aggregation for the topics presented.

The number of chapters that may be associated with these four groups of topics varies greatly in the different textbooks. Also, the total number of chapters of each book is extremely variable, ranging from less than 10 to more than 20. The decision to use chapters for this study, rather than exploring TOCs at deeper levels, was based both on opportunity (e.g., time constraints, help with translations would have been needed for the books written in languages not spoken by the author) and methodological coherence. Sections and subsections may provide elements that are essential to properly understand the content of each chapter, particularly when few of them are employed. However, the choice to group topics within a single chapter, or the opposite one to use multiple chapters to deal with some topics, is an important decision authors of textbooks are asked to make when structuring a book and has therefore an inherent conceptual value. The comparison of the relative space the authors decided to devote to the four clusters of topics is conducted by attributing each chapter to one of the categories, counting them and then dividing, for each book, these numbers by the total number of chapters. Such a comparison (Figure 1) cannot capture the way topics are treated in the different books, nor the lengths of the different chapters, but graphically reporting this relative attribution allows identifying the books that most significantly differ from the others, for instance: three books written in English and many books written in other languages do not devote any chapter to soil investigation and testing; six books devote 50% or more of the chapters to geotechnical applications.

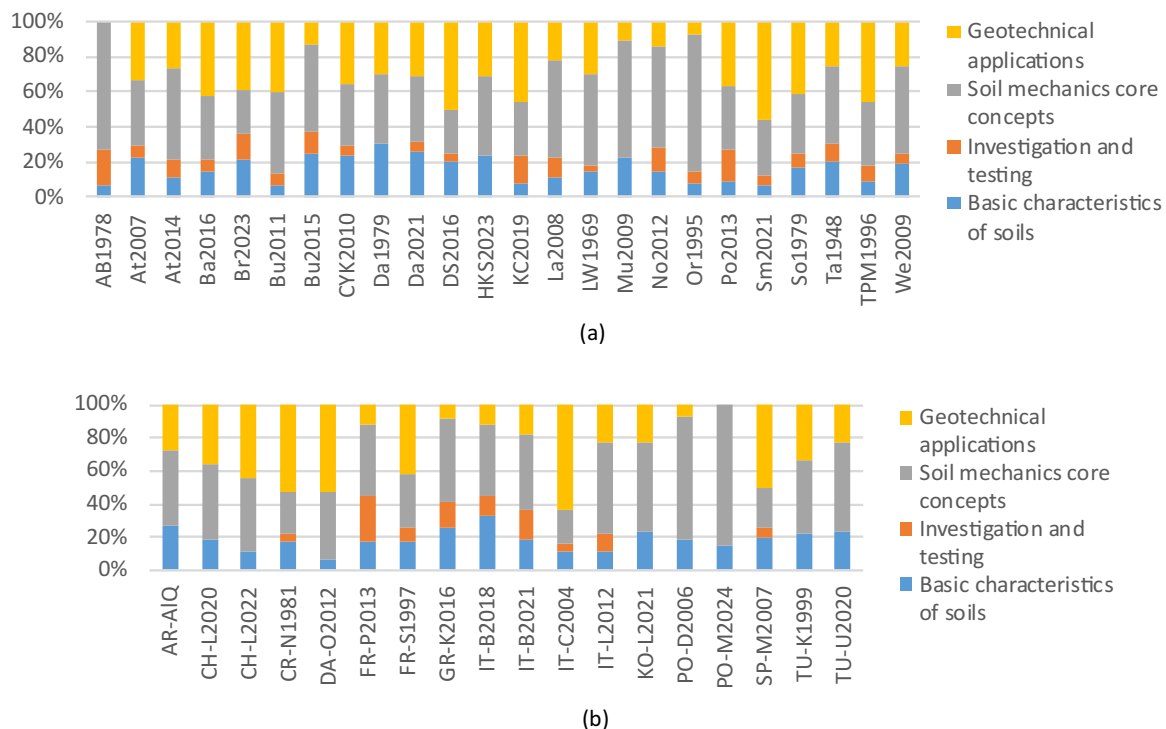


Figure 1. Relative space devoted to topics tied to basic characteristics of soils, investigation and testing, soil mechanics principles, geotechnical applications: a) books written in English and b) books written in languages other than English

4.2 Introduction and basic characteristics of soils

All books evidently start with introducing the subject of the textbook, and they continue by presenting the basic characteristics of the soils, essentially addressing soil physical properties and soil classification systems. Concerning the very first chapter(s), many books start by immediately dealing with classification or index properties (e.g., *Sm2021*, *TPM1996*), or with a short chapter simply called 'Introduction' (e.g., *IT-C20024*, *SP-M2007*), yet many others clearly highlight the "point of view" of the introduction in the title of their initial chapter (see Section 4.7 for examples). The most adopted choices are the following two:

- i) introducing geotechnical engineering as a specialty branch of civil engineering (*At2007*, *CYK2010*, *HKS2023*, *LW1969*, *GR-K2016*, *IT-B2021*), in two cases including an historical narration (*Da2021*, *DS2016*);
- ii) dealing with the origin and formation of soils and rocks (*At2014*, *Ba2016*, *Da1979*, *So1979*, *We2009*, *PO-D2006*), in a few cases specifically mentioning geology in the title of either the first (*FR-P2013*) or the second (*Bu2011*, *CYK2010*, *So1979*) chapter.

4.3 Soil investigation and testing

Soil investigation and testing is a topic that may be presented in different positions within the sequence of topics, depending on what exactly it refers to (i.e., soil exploration, laboratory testing, in-situ testing), as well as on the way it is addressed in relation to the core concepts of soil mechanics and on its use for addressing geotechnical problems.

Soil exploration, when treated, is mostly placed either after the chapters dealing with the basic characteristic of soils (*Bu2011*, *Bu2015*, *Ta1948*, *TPM1996*) or after the chapters dealing with soil mechanics core concepts (*DS2016*, *KC2019*, *Sm2021*, *So1979*, *We2009*). In two cases this subject is presented at the beginning of the book, before soil identification and classification (*CYK2010*, *FR-P2013*), and in another two cases at the very end of the book, after the geotechnical applications (*Da2021*, *Po2014*).

In-situ testing, when treated, is typically placed in the second part of the book, after the chapters dealing with soil mechanics (*At2007*, *KC2019*, *La2008*, *FR-P2013*, *GR-K2016*, *IT-B2021*, *IT-L2012*, *SP-M2007*), in the part devoted to geotechnical applications (*FR-S1997*) or after that, at the end of the book (*Ba2016*, *Po2014*). Exceptions include two books written in English (*At2014*, *Br2023*) and two books written in other languages (*CR-N1981*, *IT-C2004*), in which this topic immediately follows the introductory chapters.

Names used in the books written in English for chapters dealing with soil exploration and in-situ testing include soil (*Bu2011*, *Bu2015*, *Po2014*, *Sm2021*, *We2009*), ground (*At2014*, *KC2019*) and subsoil investigation (*Da2021*, *DS2016*, *Ta1948*), soil and rock investigation (*So1979*), soil exploration (*TPM1996*), site investigation (*Ba2016*, *Br2023*, *KC2019*, *Po2014*, *We2009*) or exploration (*CYK2010*), in-situ testing or investigation (*Br2023*, *La2008*, *Po2014*), field testing (*We2009*).

Laboratory testing for characterizing the mechanical behaviour of soils is explicitly presented in stand-alone chapters in a minority of textbooks (9 written in English, 5 in other languages), mostly when theoretical soil mechanics concepts are addressed (*At2007*, *At2014*, *AB1978*, *Br2023*, *HKS2023*, *LW1969*, *No2013*, *Or1995*, *Po2014*, *IT-B2018*), in three cases at the very end of that part (*FR-P2013*, *GR-K2016*, *IT-B2021*).

4.4 Soil mechanics core concepts

The core of soil mechanics textbooks are soil mechanics concepts that characterize the discipline. Many of these core concepts are deeply interconnected and, in many cases, it is difficult to draw clear lines separating specific topics from each other, or to group these concepts coherently into broader themes, or even to agree on common names for soil mechanics topics, concepts and themes. For this very reason, I think it is relevant to try reporting and clustering these within a sort of map of soil mechanics core concepts treated in textbooks.

My efforts in this direction have led me to the definition of seven main soil mechanics themes, to which concepts and topics covered in textbooks can be associated. They are listed here below, together with the main concepts they include.

- A. **Stresses and strains in soils** (including continuum mechanics basic concepts, stress paths, principle of effective stress, pore pressures, total stress, drained and undrained conditions)
- B. **In-situ stresses** (including initial stresses and stress distribution below the ground surface, hydrostatic water pressures, stresses from surface loads, changes of stresses)
- C. **Groundwater flow** (including flow in porous media, hydraulics of soils, stationary and transient conditions, one-dimensional and multi-dimensional flow)
- D. **Stress-strain relationships** (including behaviour of material, elastic theory, constitutive models, deformation behaviour, soil behaviour in shear)
- E. **Volumetric compression** (including volume change behaviour, compressibility, one-dimensional compression, soil settlements)
- F. **Consolidation** (including pore pressures during undrained loading, one-dimensional consolidation, rate of consolidation, settlements of fine-grained soils)
- G. **Shear strength** (including shear strength properties, critical state, peak states, drained and undrained shear strength)

This subdivision is surely arbitrary, as other educators may think that fewer or more themes, or a different type of grouping, can be used. In my proposed classification, continuum mechanics theory and stresses associated with the presence of water in the soil (theme A) and stress distributions in the ground (theme B) are two different themes because in the first case stresses (and strains) are discussed at the level of the representative elementary volume, while in the second case the space below the ground surface is explicitly considered. All the 42 analysed textbooks deal with these concepts, many textbooks (16 books) devote at least one chapter to both themes. The presence of water in the soil is key for many concepts associated with themes A and B, yet when the movement of the water in the soil pores is explicitly addressed, a different theme is considered (theme C). All 42 textbooks devote one or more chapters to groundwater flow. Stress-strain relationships could have been defined as a very wide theme associated with the presentation of elastic and elastic-plastic models, and such a theme could in principle include all types of soil deformations due to stress changes as well as failure (critical) states. However, differentiating between deformations induced by shear (deviatoric) stresses (theme D) and volumetric compression or swelling (theme E) allows to explicate the different stress-strain behaviour in the two cases. Consolidation (Theme F), despite being associated with volumetric compression, presents a clearly distinct soil feature associated with a foundational soil mechanical concept: time-dependent deformations due to the dissipation excess pore pressure. Finally, shear strength (theme G), another key concept for the mechanical characterization of soils, deserves to be mentioned separately and not only as a component of an elastic-plastic constitutive law. Slightly more than half of the books (24 books) include chapters that can be classified as dealing with stress-strain relationships. Almost all books (38 books) devote chapters to compression and consolidation; in some cases (10 books) these are presented within the same chapter. Almost all books (38 books) have chapters dealing with soil failure and shear strength.

Figure 2 shows a representation of the seven themes and of the soil mechanics concepts and topics they are mainly associated with, clustered around the theme. At times, some concepts are reported more than once, using slightly different terms, to explicitly consider wording used in the chapter titles of textbooks analysed herein. Adopting another type of representation, Figure 3 shows how these themes are addressed in each book. The capital letters associated with each theme (A to G) are listed in the order in which they appear in the TOC of each book, using different colours to enhance comprehension, as a sort of DNA sequence of the textbook in relation to the themes defined. These sequences portray how the book's authors decided to present to the readers the soil mechanics topics deemed most relevant.

The number of chapters used to address soil mechanics core concepts ranges from 4 to more than 10. At first sight, it may appear that each textbook has its own way of arranging these topics. However, some trends may be outlined. The first three themes (A to C) are typically preceding the other ones. When general concepts related to stresses and strains are present, they find a space in the first chapters of the sequence. However, a large number of books written in English start with a chapter presenting concepts related to groundwater flow (10 books). Concerning the first chapters of the books written in other languages, there is a wide distribution between all three themes: stresses and strains in soils (9 books), in-situ stresses (4 books), groundwater flow (5 books). Themes D to G are presented in a lot of different configurations. The only very common sequence that appears in many textbooks is volumetric compression and consolidation, either in the same chapter (7 books) or one after the other (4 books). Often, shear strength is concluding the sequence of these seven themes.



Figure 2. Proposed representation of the main soil mechanics themes (in bold) and of the associated concepts and topics addressed in the analysed textbooks

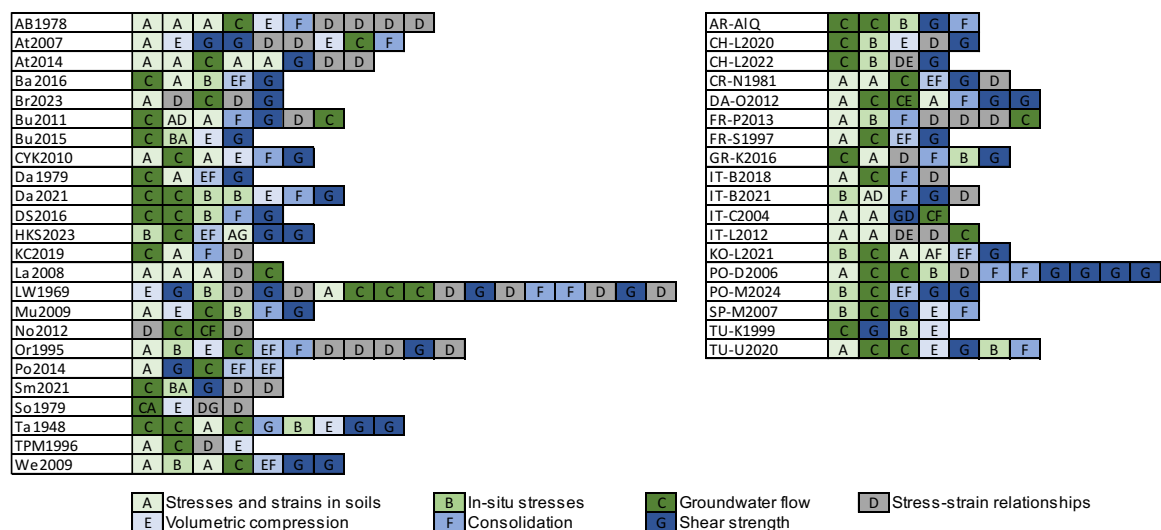


Figure 3. Proposed representation of the sequences of soil mechanics chapters in each textbook, classified according to the themes presented and ordered as they appear in the book

4.5 Geotechnical applications

Besides presenting fundamental soil mechanics, many of the textbooks listed herein also introduce the readers to basic concepts of geotechnical applications, by means of specific chapters devoted to them. As already mentioned, this is true also for many books titled 'Soil mechanics' or anyway lacking the words geotechnical or foundations in their title (*Ba2016, Da1979, KC2019, LW1969, Po2014, Sm2021, Ta1948, TPM1996, CH-G2022, CH-L2020, CH-S, FR-S1997, TU-K1999, TU-U2020*).

The main geotechnical applications addressed in textbooks are, as expected, the following three: i) foundations, ii) retaining structures, and iii) slope stability. In addition, some books also address other topics: earthworks (*Ba2026, KC2019, CR-N1981, IT-C2004*), soil improvement (*Br2023, DS2016, LW1969, IT-C2004*), geosynthetics (*Br2023, Da2021, IT-C2004*), earthquake engineering (*Br2023, CH-G2022, CH-L2020*), tunnelling (*At2007*), dams (*Ta1948, TPM1996*), geoenvironmental engineering (*Br2023*), erosion and scour (*Br2023*), road geotechnics (*FR-S1997*). Only few books written in English do not deal with geotechnical applications (*AB1978, Bu2015*) or present them very briefly in a final chapter as an introduction to more specialised textbooks (*Mu2009, No2013, Or1995*). Slightly more are these purely soil mechanics books written in other languages (*AR-A2019, FR-P2013, GR-K2016, IT-B2018, IT-B2021, IT-N2002, KO-L2021, PO-D2006, PO-M2024*).

4.6 Trends over time

Books with multiple editions published over time, with enough time difference among them, can be analysed to understand the decisions made by the authors in updating the content. An interesting case study is the book *An introduction to geotechnical engineering* (*HKC2023*), whose first edition was published in 1981 by Holtz and Kovacs. The first edition of the book was: *'intended for use in the first of a two-course sequence in geotechnical engineering usually taught to third- and fourth-year undergraduate civil engineering students. We assume the students have a working knowledge of undergraduate mechanics [...] knowledge of basic geology, although helpful, is not essential. We introduce the "language" of geotechnical engineering in the first course'*. The most significant change that occurred in these 40 years (in fact between the 2nd edition published in 2011 and the last one) is the addition of three chapters devoted to shallow foundations, lateral earth pressures and earth retaining structures, and deep foundations. The presentation of the last edition reads as follows: *'To place theory into context, the engineering significance of the property being discussed is presented, along with why the property is needed, how it is determined or measured, and how it is used in specific design situations.'* Other (less significant but nevertheless important) changes also have occurred. In the initial part, the first two editions had a chapter on clay minerals of soil structures, not present in the last edition; starting from the second edition a new chapter on geology, landforms and the origin and evolution of geomaterials was added. Some changes in names and some grouping occurred in the central chapters devoted to the soil mechanics core concepts yet keeping the same sequence of topics: water in soils, compressibility and consolidation, failure. Finally, from the 2nd edition, in addition to the two chapters already dealing with failure theories and shear strength, a final chapter is present on Advanced topics in shear strengths of soils and rocks.

Another case study is *Craig's soil mechanics* (*KC2020*), whose first and last editions were published in 1974 and 2020, respectively. Besides the significantly increased space devoted to geotechnical applications, the most significant changes in the structure of the first part of the textbook, i.e., the part addressing soil mechanics concepts, occurred between the 7th ed. (2004) and the 8th ed. (2012), which is the first edition co-authored by J. Knappett, who writes: *'I felt that the time was right for a major update [...] though I have tried to maintain the clarity and depth of explanation which has been a core feature of previous editions. [...] It is still intended primarily to serve the needs of the undergraduate civil engineering student and act as a useful reference through the transition into engineering practice. However, inclusion of some more advanced topics extends the scope of the book, making it suitable to also accompany many post-graduate level courses.'* In terms of structure and focus of part I, for the first time called 'development of a mechanical model for soil', the changes were significant. Only the first three chapters retained titles and position: basic characteristics of soils, seepage, effective stress. Shear strength and stresses and displacements, are preceded by a chapter on consolidation, previously addressed in the last chapter of this theoretical part, and these concepts are presented in one chapter titled: soil behavior in shear. Part I of the book ends with two chapters devoted to ground investigation (previously placed after foundations and slope stability) and in-situ testing. Lateral earth pressures, previously presented as an autonomous chapter in the first part, are inside the chapter in part II devoted to retaining structures.

4.7 Specific points of view

A few textbooks may be considered unusual as they intentionally approach the introduction to soil mechanics from a specific point of view, and this intention is often stated in the title of the book.

- *The mechanics of soils: an introduction to critical state soil mechanics* (AB1978), and *Soil mechanics in the light of critical state theories* (Or1995), address soil mechanics mainly considering the framework of critical state theory. It must be noted that these are not the only books treating critical state soil mechanics, which is indeed specifically mentioned in the name of a chapter in other four books (At2007, At2014, Bu2011, Sm2021) but is also treated in many other textbooks when soil constitutive modelling or shear strength concepts are presented.
- *Fundamentals of soil mechanics for sedimentary and residual soils* (We2009). The need for such a book lies in the fact that ‘*despite its prevalence in under-developed parts of the United States and most tropical and sub-tropical countries, residual soil is often characterized as a mere extension of conventional soil mechanics in many textbooks. [...], with the rapid growth of construction in these regions, it is essential to gain a fuller understanding of residual soils [...] based on an integrated approach to the study of residual and sedimentary soils.*’
- *Geotechnical engineering: unsaturated and saturated soils* (Br2023). ‘Why this book?’ is the title of the first section of the first chapter of the book, wherein the author reports a quote by Albert Einstein ‘*Things should be made as simple as possible but not a bit simpler than that*’ and states ‘*The first driving force for writing it was the coming of age of unsaturated soil mechanics: [...] to introduce geotechnical engineering as dealing with true three-phase soils while treating saturated soil as a special case, rather than the other way around. The second driving force was to cover as many geotechnical engineering topics as reasonably possible in an introductory book, to show the vast domain covered by geotechnical engineering.*’
- *Soil mechanics: a one-dimensional introduction* (Mu2009). The author states: ‘*in the context of teaching principles of soil mechanics to undergraduates in the early years of their civil engineering degree programmes, I believe that there is advantage to be gained in trying to integrate [...] teaching of properties of engineering materials to which the students are being exposed at the same time. [...] [which] prompted me to explore a [...] one-dimensional theme for the presentation of many of the key concepts of soil mechanics: density, stress, stiffness, strength and fluid flow. This one-dimensional approach to soil mechanics has formed the basis for an introductory course of ten one-hour lectures with ten one-hour problem classes and one three-hour laboratory afternoon for first-year civil engineering undergraduates.*’

4.8 Other comments

The topic of compaction appears in many soil mechanics textbooks, albeit not in most of them. When it is addressed, its relative position varies significantly. Indeed, this topic is at times discussed after presenting the basic characteristics of soils (DS2016, HKS2023, CYK2010, Bu2011, Da2021, PO-D2006, KO-L2021), at times when discussing soil mechanics concepts (Bu2015, AR-A2019, TU-U2020, IT-C2004), and at other times when the geotechnical applications are presented (Br2023), mostly at the very end of the book (Sm2021, We2009). To explain this finding, one may consider that this topic relates to the realization of geotechnical works with a long empirical tradition for situations where the soil is used a construction material in earth fills or embankments, yet the behaviour of soils undergoing compaction can be explained theoretically only by considering the mechanics of soils in partially saturated conditions. Only a minority of textbooks devote at least one full chapter to unsaturated soil mechanics (At2007, At2017, Br2023, FR-P2013, PO-M2024). Therefore, it should not come as a surprise if many authors decide not to treat soil compaction in textbooks that introduce students to the main concepts of soil mechanics without considering unsaturated conditions such as, among others: the oldest textbooks written in English (Ta1948, LW1969, So1979, TPM1996), with the notable exception of the textbook written by Holtz et al. (HKS2023) since its first edition in 1981. The titles of these chapters may also be indicative of how this subject is treated. In the four books where this chapter is not simply called ‘Compaction’ or ‘Soil compaction’ the following titles are used: ‘Compaction and stabilization of soils’ (HKS2023); ‘Excavation, grading, and compacted fill’ (CYK2010); ‘Soil compaction, highway foundation design and ground improvement’ (Sm2021).

Almost all books introduce the theoretical concepts for soils in general, rather than devoting entire chapters at discussing aspects of the mechanical behaviour of only sands or clays. Exceptions to this rule are the following: all the three textbooks written by Portuguese or Brazilian authors (PO-D2006, PO-

M2024, *Or1995*) and the old textbook by Taylor (*Ta1948*), which present the concept of soil strength separately for sands and clays, with *PO-M2024* also calling one chapter “Compressibility and consolidation of clay layers” and *PO-D2006* devoting the final chapter of the book to the “Behaviour of some typical soils”.

5 Concluding remarks

The research conducted herein had the aim to identify commonalities and divergences in topic coverage and topic sequence in introductory soil mechanics and geotechnical engineering textbooks written in different times and different languages. The insights gained from this comparative analysis could serve as a valuable resource for educators seeking to refine their course content and could also potentially inform future textbook editions. Different geotechnical educators, reading in this article, will probably focus their attention to different findings, e.g., landmark books, intriguing sequences of topics, specific names used to address concepts, new references to explore. All of them will hopefully find some good “food for thought” for their educational activity.

As a byproduct of this study, a relatively long list of textbooks, written in English and in other languages, was compiled and discussed. Even if the search that led to this list cannot be considered comprehensive or systematic, it is the opinion of the author that most of the relevant books, especially the ones written in English, have been considered herein. This list may prove useful to many, as a source of information on textbooks currently available. For instance, books previously unknown to some educators may be discovered as resources of educational material suiting their own style of teaching. Possibly, this list can also be used as a sort of reading list for geotechnical engineering teachers wanting to deepen their knowledge on specific aspects of the discipline or to delve deeper into the historical writings of educators from the past. It would not be surprising if some of the readers may find this list, as such, the most important product of this article.

Acknowledgements

Thanks to all the members of the ISSMGE Technical Committee 306 “Geo-engineering education” who have helped me in gathering the materials used in this article, and special thanks to the Chair of TC306, Marina Pantazidou, for her motivation to address this topic, for many inspirational conversations, and for personal notes passed to me specifically for this study.

References

- Al-Qasabi, S.A.F. (2019). ميكانيكا التربة., Egypt.
- Atkinson, J.H. (2007). The Mechanics of Soils and Foundations, 2nd ed. Taylor & Francis, Oxon, UK.
- Atkinson, J.H. (2014). Fundamentals of Ground Engineering. CRC Press, Boca Raton, USA.
- Atkinson, J.H., Bransby, P.L. (1978). The Mechanics of Soils: An Introduction to Critical State Soil Mechanics. McGraw-Hill, New York, USA.
- Barnes, G. (2016). Soil Mechanics: principles and practice, 4th ed. Bloomsbury Publishing, London, UK.
- Berardi, R. (2021). Fondamenti di geotecnica, 4th ed. CittàStudiEdizioni, Tonino, Italy.
- Briaud, J.L. (2023). Geotechnical Engineering: Unsaturated and Saturated Soils, 2nd ed. Wiley, Hoboken, USA.
- Budhu, M. (2011). Soil mechanics and foundations, 3rd ed. Wiley, Hoboken, USA.
- Budhu, M. (2015). Soil Mechanics Fundamentals, metric version. Wiley, Hoboken, USA.
- Burghignoli, A. (2018). Meccanica delle terre. Hevelius edizioni, Benevento, Italy.
- Coduto, D.P., Yeung, M.R., Kitch, W.A. (2010). Geotechnical Engineering: Principles & Practices, 2nd ed. Pearson, London, UK.

- Colombo, P., Colleselli, F. (2004). Elementi di geotecnica, 3rd ed. Zanichelli, Bologna, Italy.
- Das, B.M. (1979). Introduction to soil mechanics. Ames: Iowa State University Press, Ames, USA.
- Das, B.M. (2021). Principles of Geotechnical Engineering, SI edition, 10th ed. Cengage, Boston, USA.
- Das, B.M., Sivakugan, N. (2016). Fundamentals of Geotechnical Engineering, 5th ed. Cengage, Boston, USA.
- De Sousa Pinto, C. (2006). Curso básico de mecânica dos solos, 3rd ed. Oficina De Textos, Sao Paulo, Brazil.
- Holtz, R.D., Kovacs, W.D., Sheahan, T.C. (2023). An introduction to geotechnical engineering, 3rd ed. Pearson, London, UK.
- Kavvadas, I.M. (2016). Στοιχεία εδαφομηχανικής, 2nd ed. Συμμεων εκδοσεις, Athens, Greece.
- Knappet, J.K., Craig, R.F. (2019). Craig's Soil Mechanics, 9th ed. Routledge, Milton, UK.
- Kumbasar, V., Kip, F. (1999). Zemin Mekaniği Problemleri. Çağlayan Kitabevi, Istanbul, Turkey.
- Lambe, T.W., Withman, R.V. (1969). Soil Mechanics. John Wiley & Sons, Hoboken, USA.
- Lancellotta, R. (2008). Geotechnical Engineering, 2nd ed. CRC Press, Boca Raton, USA.
- Lancellotta, R. (2012). Geotecnica, 4th ed. Zanichelli, Bologna, Italy.
- Lee, I.M. (2021). 토질역학의 원리, 3rd ed., Korea.
- Li, G., Zhang, B., Yu, Y. (2022). 土力学, 3rd ed. Tsinghua University Press, Beijing, China.
- Liu, S. (2020). 土力学, 5th ed. China Architecture & Building Press, Beijing, China.
- Matos Fernandes, M. (2024). Mecânica dos Solos. Conceitos e Princípios Fundamentais, 6th ed. U.Porto Press, Porto, Portugal.
- Mitchell, J.K., Soga, K. (2005). Fundamentals of Soil Behavior, 3rd ed. Wiley.
- Muir Wood, D. (2009). Soil mechanics: A one-dimensional introduction. Cambridge University Press.
- Muzas Labad, F. (2007). Mecánica del suelo y cimentaciones. Fundación Escuela de la Edificación.
- Nonveiller, E. (1981). Mehanika tla i temeljenje građevina. Školska knjiga, Zagreb.
- Nova, R. (2013). Soil Mechanics. Wiley, Hoboken, USA.
- Ortigao, J.A.R. (1995). Soil Mechanics in the Light of Critical State Theories. Routledge, Milton, UK.
- Ovesen, N.K. (2012). Lærebog i Geoteknik, 2nd ed. Polyteknisk Forlag, Lyngby, Denmark.
- Plumelle, C. et al. (2013). Théorie et pratique de la géotechnique. Le Moniteur Editions, Gentilly, France.
- Powrie, W. (2013). Soil Mechanics: concepts and applications, 3rd ed. CRC Press, Boca Raton, USA.
- Schlosser, F. (1997). Eléments de mécanique des sols, 2nd ed. Presses de l'école nationale des Ponts et Chaussées, Paris, France.
- Smith, I. (2021). Smith's Elements of Soil Mechanics, 10th ed. Wiley-Blackwell, Hoboken, USA.
- Sowers, G.F. (1979). Introductory soil mechanics and foundations, 4th ed. Macmillan, New York, USA.
- Taylor, D.W. (1948). Fundamentals of soil mechanics. Asia Publishing House, Bombay, India.
- Terzaghi, K., Peck, R.B. (1948). Soil Mechanics in Engineering Practice. John Wiley, Hoboken, USA.
- Terzaghi, K., Peck, R.B., Mesri, G. (1996). Soil Mechanics in Engineering Practice, 3rd ed. Wiley, Hoboken, USA.
- Uzuner, B.A. (2020). Temel Zemin Mekaniği: Çözümlü Problemlerle. Derya Kitabevi, Gölcük, Turkey.
- Wesley, L.D. (2009). Fundamentals of soil mechanics for sedimentary and residual soils. Wiley, Hoboken, USA.

Author's bio

Michele Calvello, University of Salerno, Italy

Michele Calvello is full professor in geotechnical engineering at the University of Salerno (Italy), where he currently teaches “soil mechanics” and “landslide risk”. He graduated with honours in civil engineering from Università della Basilicata (Italy) in 1997, and he earned a PhD degree from Northwestern University (USA) in 2002. His main research interests are focused on the engineering analysis of geotechnical boundary value problems and on the analysis and management of landslide risk, with special attention devoted to the following inter-disciplinary topics: early warning systems, landslide zoning, risk perception, risk education and community resilience. Currently he is the president of “LandAware – the international network on landslide early warning systems”, the Principal Investigator of the Horizon Europe project “The HuT. The Human-Tech Nexus – Building a Safe Haven to cope with Climate Extremes”, and the co-Coordinator of the LARAM School, an International School for PhD students on “LAndslide Risk Assessment and Mitigation”. He is a member of the Editorial Board of the journals Georisk, Geoenvironmental Disasters, Landslides and Rivista Italiana di Geotecnica. He is Secretary of the ISSMGE Technical Committee TC-306 “Geo-Engineering Education”.

Developing concept inventories for Geotechnical Engineering

A. Kirsch¹, W. Fellin² & R. Sonnenberg³

¹*FH Aachen - University of Applied Sciences Aachen, Germany*
kirsch@fh-aachen.de

²*University of Innsbruck, Austria*
wolfgang.fellin@uibk.ac.at

³*Magdeburg-Stendal University of Applied Sciences, Germany*
rene.sonnenberg@h2.de

This paper explores the development of geotechnical concept inventories to assess core competencies in civil engineering education. The study is motivated by the need to define essential geotechnical skills and to establish effective assessment methods. To address these challenges, the authors relied on the teaching network *GeNIaL*, which brings together geotechnical educators from Germany, Austria and Switzerland. A systematic approach was taken to identify key skills, formulate learning outcomes, develop test questions and conduct a survey across six universities. The study used peer teaching as an active learning strategy to improve student understanding. The survey revealed variations in student understanding and highlighted misconceptions. The findings provide insights for refining assessment tools and advancing the development of concept inventories tailored to geotechnical engineering education. The study emphasises the importance of structured formative assessment in shaping effective teaching strategies and improving learning outcomes.

Keywords: Peer instruction, Core skills, Concept inventory, Fundamental geotechnical concepts, Geotechnical engineering education

1 Introduction

1.1 Motivation

There is an ongoing debate about what skills civil engineering students should (or should not) acquire in soil mechanics and geotechnics. Consequently, this issue has been the subject of several publications.

Interest in this topic often arises when people start teaching. Thus, it was issued within the teaching network *GeNIaL* (short for the German version of *Geotechnics Network for Innovation in Teaching*). This network was founded in 2022 to share ideas and knowledge about suitable teaching innovations in the field of geotechnical engineering (Kluge et al., 2023). By now the network currently comprises 13 geotechnical professors from all over Germany, Austria and Switzerland. Soon the question emerged, how to simply assess and address whether students of civil engineering achieve certain core skills, even though they do not specialise in geotechnical engineering.

Initially the aim was to define *concept inventories* as an instrument to assess students' knowledge of a specific set of fundamental geotechnical concepts (cf. Section 3.6). This proved to be difficult for the geotechnical objectives. Other methods of application were considered, such as peer teaching, review of learning outcomes and developing well defined interfaces between different courses within the faculty. Last but not least, it was also considered implementing these core skills into professional guidelines for engineering education.

The following approach was adopted within the network of *GeNiaL*: First, a literature review on geotechnical core skills for civil engineers was conducted. Afterward, corresponding learning outcomes were formulated. Following this, suitable test questions were developed to cover the selected outcomes. Next, a survey was carried out to test these questions through some of the associated universities of the *GeNiaL* network. This survey is analysed in this paper and suggestions for further steps are drawn.

1.2 Geotechnical core skills for civil engineers

Every lecturer or practitioner in geotechnical engineering at some point develops a perception about the most essential geotechnical skills for civil engineers. This perspective is commonly based on personal academic and professional experience and is influenced by demands of professional bodies and the society.

Some of those perceptions were presented during the 2012 International Conference *Shaking the foundations of geo-engineering education*, e.g. Fiegel (2012). Most authors focus on the education and necessary skills of *geotechnical* engineers (e.g. Baldwin, 2012). Often, it is not clearly defined what the most essential skills are that every graduate from *civil* engineering should be able to demonstrate.

Atkinson (e.g. 2008; 2012) suggested a number of core skills for geotechnical *professionals*. The identified core skills are related to different levels of professional involvement, including school, undergraduate degree, first professional experience, postgraduate degree and research. These key skills were furthermore distinguished between civil engineering in general, geotechnical engineering, engineering geologists and geologists. According to Atkinson (2012), a first-degree civil engineer should have acquired the following geotechnical skills:

- Material behaviour and properties, such as measuring the angle of internal friction or the strength of clay, relating undrained shear strength to index properties, relating pore pressure to water content and even doing sandcastle experiments.
- Ground investigations and subsoil modelling, including using engineering terms for describing soil and rock.
- Groundwater, comprising drawing of simple flownets, calculating flow rates and determining pore water pressure at any point in a flownet.

Atkinson (2016) even dedicated the 1st John Burland Lecture to exploring the question of what basic geotechnical engineering skills graduates should possess. In this lecture, he elaborated further and extended the list. It now includes modelling aspects for the ground, the evaluation of design parameters, and the design of simple slopes and foundations.

Fiegel (2012) presents specific learning objectives for essential knowledge and skills for an introductory geotechnical engineering course, following Bloom's taxonomy (Bloom et al., 1956). The topics covered by Fiegel (2012) include phase relations, geotechnical site characterisation, index properties and classification tests, soil classification, geostatic stress calculations and earth pressures, soil compaction, hydraulic conductivity, two-dimensional flow and flow nets, soil stiffness and soil strength. A detailed list of 27 lectures for an introductory course in geotechnical engineering has been suggested by Shidlovskaya & Briaud (2016). They incorporate topics such as engineering geology, rocks, unsaturated soils or geo-environmental issues.

While numerous authors have contributed to expanding the list of essentials, only few concentrated on the most critical principles. Matos Fernandes and Couto Marques (2020) for instance focussed on the link between the physical nature of soil and its corresponding index properties. They also explored the connection between these properties and the mechanical behaviour of the soil.

Soil classification, shear strength and bearing capacity are mentioned as key geotechnical engineering topics by Pantazidou (2016). However, the principle of effective stress seems to be *the big idea* (as stated by Pantazidou, 2020) or the *threshold concept* of soil mechanics (according to Phillips, 2020). Thus, it is a fundamental concept in engineering education, applicable to both general civil engineering and geotechnical disciplines.

Also, professional bodies or associations such as the German ASBau (Accreditation Association for Study Programmes in Civil Engineering) have proposed geotechnical *knowledge, proficiency and skills* for a civil engineering syllabus (ASBau, 2021). These student competencies do play a significant role in accreditation processes for study programmes in Germany. They are reviewed by the expert panels involved in the accreditation. However, these recommendations are quite general and not specifically

tailored for education purposes. Among other issues, they are open to broad interpretation and their intentions are not always clear.

A remarkable attempt to define competencies in geotechnical *numerical* analysis is reported by Lees (2015). Within the project COGAN (short for Competency in Geotechnical Analysis) approximately 1,000 (!) competence statements were developed and reviewed by an expert panel for several module areas. These statements outline what a user of numerical analysis software needs to understand in order to perform safe analyses in geotechnical engineering. The module areas include constitutive models for geomaterials, obtaining soil and rock parameters, shallow and deep foundation, and soil mechanics. The latter module itself consists of over 60 statements.

Moreover, a *Competency Tracker* was developed within the COGAN project to record and monitor the development of geotechnical practitioners. For each individual field, relevant sources, such as textbooks, publications, webpages or training courses provide an educational base for self-learners and course instructors.

2 Core skills and test questions for soil mechanics in higher education

2.1 Core skills suggested by *GeNlaL*

Based on the above, the members of *GeNlaL* worked to narrow the extensive lists down to only five most fundamental geotechnical skills. These are the skills that every graduate should acquire at university. Starting with a list of approximately 120 statements for individual learning outcomes, every member was asked to prioritise and mark down the personal *must haves*.

Keeping Bloom's taxonomy of learning outcomes (Bloom et al., 1956) in mind, the results were then reviewed in several meetings and refined by the authors. The following six core skills were finally formulated for civil engineering graduates with a first degree (Bachelor level):

They ...

- ... will be able to differentiate between the basic types of soil (clay, silt, sand, gravel, stones, blocks), assign characteristic properties to them and assess their suitability for use in construction.
- ... can select the appropriate unit weights for a given soil profile with and without groundwater and use them to calculate the total and effective stresses in the ground (vertical and horizontal).
- ... will be able to explain the non-linear stiffness of soil and calculate the settlements under a shallow foundation.
- ... can explain the models for describing the shear strength of soils and correctly select the associated parameters depending on the boundary conditions (drained and undrained).
- ... will be able to explain the differences between active, passive and earth pressure at rest and determine their distribution for a given soil profile.
- ... can determine effect of actions and resistance to an action for various geotechnical problems, both Ultimate Limit State (ULS) and Serviceability Limit State (SLS).

2.2 Development of corresponding test questions

To address the defined six core skills, the authors developed a series of multiple-choice questions. The questions should assess true understanding of fundamental geotechnical principles rather than relying solely on memorised facts or national codes of practice. They should be phrased as simply as possible, using everyday contexts. Each question should have at least one correct answer, with a maximum of four to six answer choices to accommodate audience response systems (*clicker systems*). Last, but not least, the questions should be suitable as concept inventories and/or questions for peer instruction. For concept inventories see Section 3.6.

After compiling some 50 questions relating to those six core skills, these were reviewed by *GeNlaL* for their suitability. Subsequent, the network selected ten questions according to the core skills specifically related to soil mechanics. There are two questions for each of the following topics: soil characteristics, effective stresses, soil stiffness and settlement, shear strength, and earth pressure (cf. Section 3 and Figure 1). Note, Question 4.2 (Slope angle) is based on an experiment presented by Schofield (2016).

2.3 Application in a peer instruction setting

Peer instruction is an evidence-based, student-centred pedagogical approach commonly used to enhance active learning and conceptual understanding in classrooms (Crouch, 1998; Crouch & Mazur, 2001; Fagen et al., 2002; Mazur, 1997). It involves students answering conceptual questions individually (first round), discussing their reasoning with peers, and then re-evaluating their answers (second round). This engaging method is an active learning strategy that encourages students to generate knowledge collaboratively.

For the survey, a peer instruction setting was chosen to introduce the questions to the students. For such a setting, students first answer multiple-choice (or short single-choice) questions alone. Thereafter the students are given time to analyse the problem with their neighbours and then give their answers again. Finally, both voting results and the correct solution(s) are presented, which can then be further evaluated.

The increase in understanding using peer instruction has been proven (e.g. Crouch & Mazur, 2001). According to Crouch and Mazur (2001), an initial correct response rate of approximately 35% to 70% is considered optimal for peer instruction questions. Other studies suggest a broader optimal range, e.g. a lower bound of 30% and an upper bound of 80% (cf. Technische Hochschule Augsburg, 2025). This range has been adopted for data interpretation (cf. Section 3).

If 30% to 80% of students answer correctly in the first round, the question may be considered for peer instruction. If the second round leads to an increase in correct answers, the question is ideal for peer instruction. If fewer than 30% of the student's responses are correct in the first round, it indicates poor initial understanding, making it necessary to revise the concept before proceeding. If more than 80% of students have answered correctly, the question is classified as too easy. In such case only a brief detailed explanation should be given and a second round is not necessary. Questions that are too easy weaken the effectiveness of the method.

3 Survey among six universities in the winter term 2024/25

3.1 Methodology for the survey

For the survey the ten questions were applied in a peer instruction setting. Participants were given 1 minute and 30 seconds for the first round and 2 minutes for the second round. Thus, allowing the students to familiarise with the question during the first round and ensuring enough time for interacting with their peers during the second round. Lecturers were briefed not to give any explanation beforehand and during this time. To track students' answers over two rounds, the online audience response system *Particify* (<https://ars.particify.de/>) was utilised.

The survey was rolled out between November 2024 and January 2025. A total of eight lecturers from University of Applied Sciences Aachen, Bochum, Magdeburg-Stendal and Mainz as well as from University of Innsbruck and Siegen took part in the survey.

All participating universities launched the survey in an undergraduate course, typically 3rd semester. In one instance, the survey was conducted in the 7th semester via a video conference. The participating lecturers were free to choose when to conduct the survey, either immediately at the end of a session, a few days after introducing a topic, or at the end of the term.

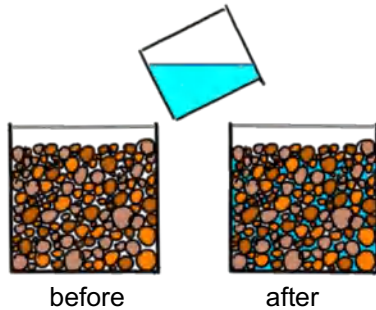
3.2 Compilation of questions and students' answers

The ten questions (correct answers in green) are presented in the following section together with the results of participating universities, see Figure 1. The answers of all students are accumulated in the figures, n denoting the total number of students that gave answers for each round. Details are given in the next section.

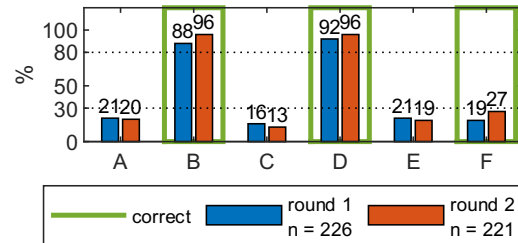
After the tests, students were invited to give feedback on the questions and explain their reasoning.

Question 1.1 (Impact of water)

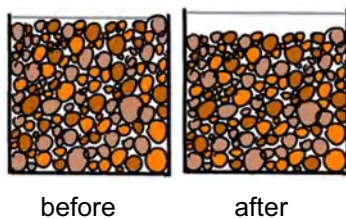
A container is filled with dry sand. By adding water, the soil is fully saturated. The packing of the soil particles does not change. Which soil parameter(s) change(s) due to the addition of water?



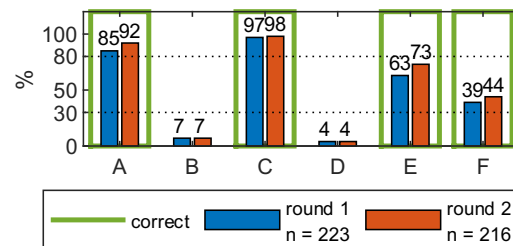
- A) Void ratio
B) Degree of saturation
C) Bulk density
D) Water content
E) Friction angle
F) Stiffness

**Question 1.2 (Impact of compaction)**

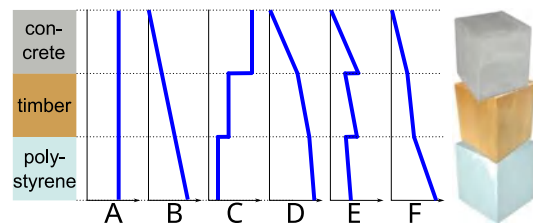
A container is filled with dry sand. The soil is compacted by shaking and tamping. Which soil parameter(s) change(s) as a result of compaction?



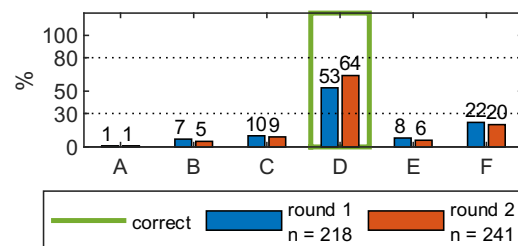
- A) Void ratio
B) Degree of saturation
C) Bulk density
D) Water content
E) Peak friction angle
F) Stiffness

**Question 2.1 (Vertical stress distribution)**

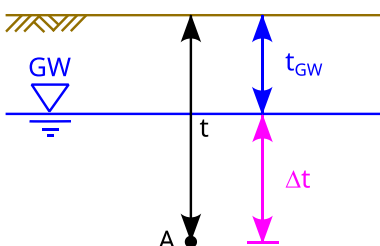
Three cubes made of concrete, wood and insulating material are stacked on top of each other to form a tower.



Which diagram shows the correct distribution of vertical stresses over the height of the tower?

**Question 2.2 (Effective vertical stress)**

The effective vertical stress at point A is calculated by:



- A) $\gamma \cdot t$
B) $\gamma' \cdot t$
C) $\gamma \cdot t_{GW} + \gamma' \cdot \Delta t$
D) $\gamma' \cdot t_{GW} + \gamma \cdot \Delta t$
E) $\gamma \cdot t_{GW} + \gamma_w \cdot \Delta t$

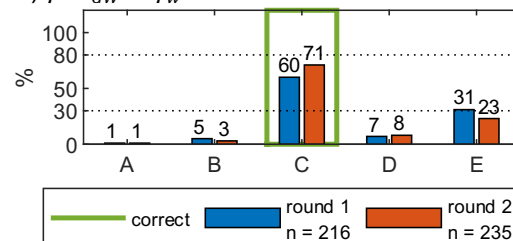
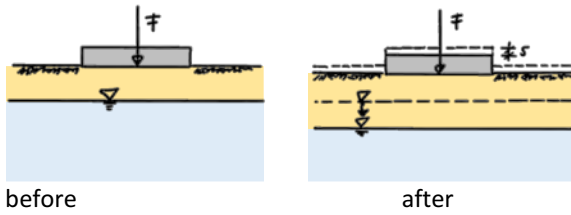


Figure 1. Questions, answers and summary of evaluation (correct answers in green)

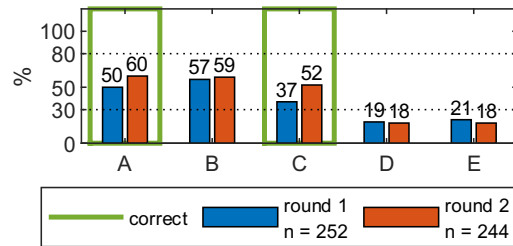
Question 3.1 (Groundwater settlement)

Why does settlement occur due to groundwater lowering?

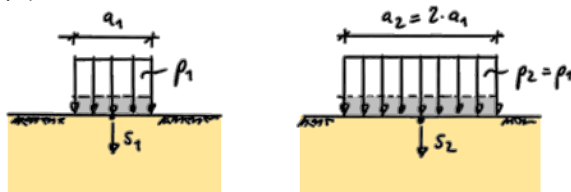


- A) Because the wet unit weight γ is greater than the buoyant unit weight γ' .
 B) Because groundwater lowering creates cavities in the subsoil.

- C) Because of increased effective stresses in the soil.
 D) Because of increased total stresses in the soil.
 E) Because the wet unit weight γ is smaller than the buoyant unit weight γ' .

**Question 3.2 (Foundation width effect)**

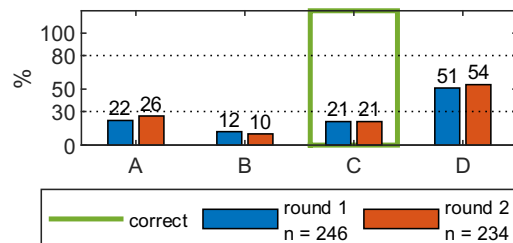
Given two strip foundations on a silty sand, the second of which is twice as wide as the first ($a_2 = 2 \cdot a_1$). An identical load is applied to both ($p_1 = p_2$).



Which conclusions are correct with respect to the expected settlements?

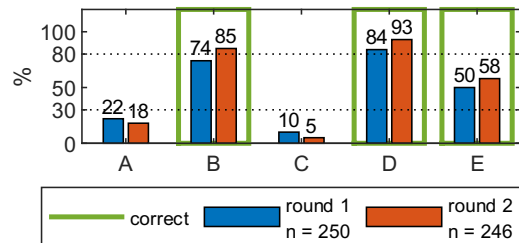
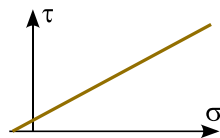
- A) The settlements under both foundations are the same, because the pressure is the same.

- B) The settlement under Foundation 1 is smaller, because the total force is reduced.
 C) The settlement under Foundation 1 is smaller, because the depth of influence is limited.
 D) The settlement under Foundation 1 is greater, because the base area is reduced.

**Question 4.1 (Soil shear strength)**

Which parameters are critical for the soil shear strength?

- A) Confined compression modulus
 B) Cohesion
 C) Young's modulus
 D) Friction angle
 E) Normal stress

**Question 4.2 (Slope angle)**

Sand is filled into two containers, one completely dry, the other one completely filled with water. When the first container is slowly tilted, the sand slips forming a slope angle β that is similar to the friction angle φ of the loosely packed sand.



If the water-filled sand container is slowly tilted, the slope angle β of the sand in this container is:

- A) ... greater than for dry sand.
 B) ... the same as for dry sand.
 C) ... smaller than for dry sand.
 D) ... equal to zero (flat surface).

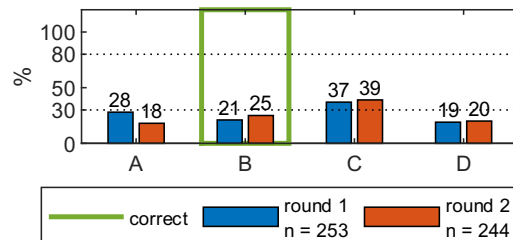


Figure 1 (cont.). Questions, answers and summary of evaluation (correct answers in green)

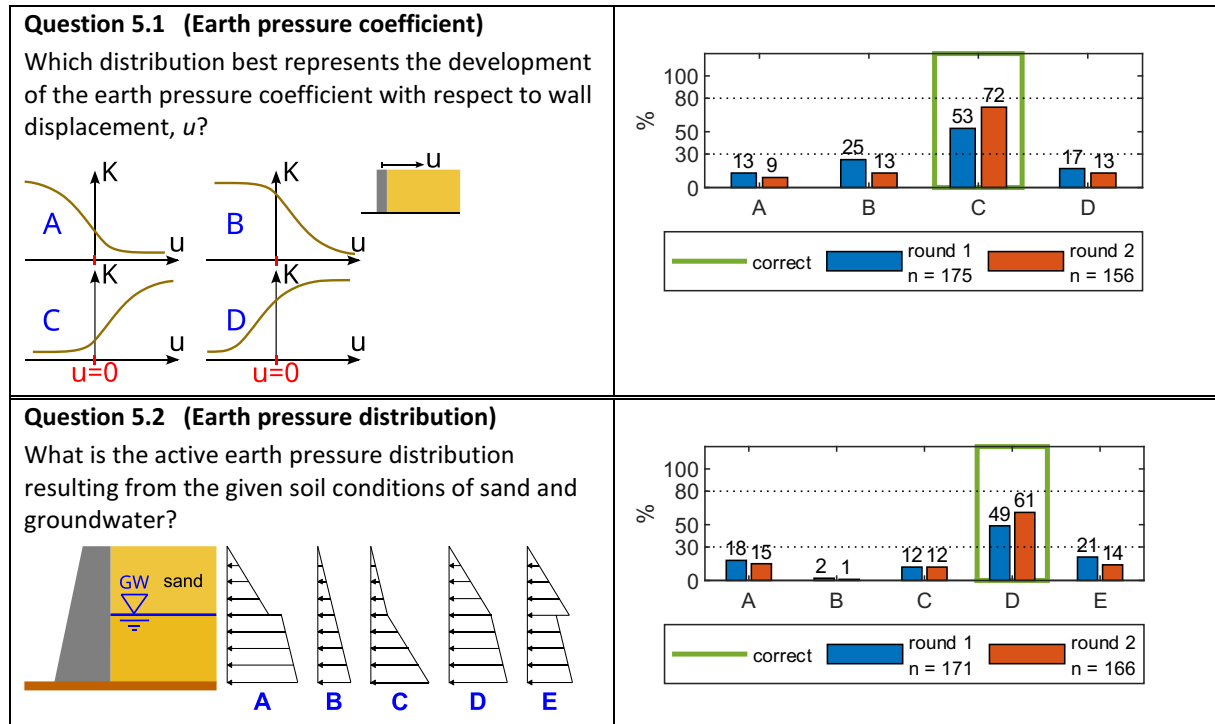


Figure 1 (cont.). Questions, answers and summary of evaluation (correct answers in green)

3.3 Evaluation of the survey

The results were evaluated according to the following approach. Let α_{ij} be 1 if a student of university j selected answer option i of a question, and 0 otherwise. The index i corresponds to the answer options, ranging from A to D, E, or F, depending on the number of choices provided for the respective question. The index j ranges from 1 to $N = 6$, representing the total number of participating universities. The number $a_i = \sum_j \alpha_{ij}$ indicates how often the answer option i was selected by the students and n denotes the total number of students who responded in each round. Note, the numbers of students may differ between the two rounds, e.g. if not all students replied within the given time frame.

The plotted relative values in Figure 1 are computed by a_i/n . For example, the evaluation of round 2 of Question 5.2 (Earth pressure distribution) is shown in Table 1. Note that $\sum a_i$ differs from n because students can choose more than one answer options, in general $\sum a_i \geq n$ holds. This implies that $\sum \frac{a_i}{n}$ may also be $\geq 100\%$.

Table 1. Evaluation of Question 5.2, round 2

	$i = A$	B	C	D	E	$\sum a_i$	n
all students: $a_i = \sum_j \alpha_{ij}$	25	1	20	102	23	171	166
a_i/n in %	15	1	12	61	14		

To obtain a single representative number for each question per round, the number of correct answers is related to the number of all answers following Equation (1).

$$c_j = \frac{\sum_i \alpha_{ij} w_i}{\sum_i \alpha_{ij}} \quad (1)$$

The factor w_i is set to 1 if the answer option i is correct and zero otherwise, as shown in the following tables.

Table 2 and Table 3 illustrate this computation for Question 5.2 (Earth pressure distribution with one correct answer) for round 2 and Question 1.2 (Impact of compaction with four correct answers) for round 1 at University 2.

Table 2. Computation of relative number of correct answers c_j for Question 5.2, round 2, for the students of University $j = 2$

	$i = A$	B	C	D	E	$\sum_i \alpha_{ij} w_i$	$\sum_i \alpha_{ij}$	$c_j = \frac{\sum_i \alpha_{ij} w_i}{\sum_i \alpha_{ij}}$ in %
w_i	0	0	0	1	0			
α_{ij}	13	1	9	30	5	30	58	52

Table 3. Computation of relative number of correct answers c_j for Question 1.2, round 1, for the students of University $j = 2$

	$i = A$	B	C	D	E	F	$\sum_i \alpha_{ij} w_i$	$\sum_i \alpha_{ij}$	$c_j = \frac{\sum_i \alpha_{ij} w_i}{\sum_i \alpha_{ij}}$ in %
w_i	1	0	1	0	1	1			
α_{ij}	38	2	44	2	32	11	125	129	97

The results of all universities (anonymised as 1 to $N = 6$) are presented in Table 4. Questions with correct answers between 30% and 80% in the first round are marked bold and in green. Questions are marked in red if the peer instruction led to a decrease in the correct answer rate.

Table 4. Percentage of correct answers for both rounds (r1 and r2) and their difference Δ

Univ.	1.1			1.2			2.1			2.2			3.1			3.2			4.1			4.2			5.1			5.2		
	r1	r2	Δ	r1	r2	Δ	r1	r2	Δ	r1	r2	Δ	r1	r2	Δ	r1	r2	Δ	r1	r2	Δ	r1	r2	Δ	r1	r2	Δ	r1	r2	Δ
1	81	83	2	96	98	2	67	69	2	79	72	-7	52	60	8	20	15	-5	84	87	3	14	17	3	49	69	20	61	57	-4
2	78	82	4	97	97	0	30	38	8	48	65	17	48	58	10	44	40	-4	98	98	0	54	75	21	64	75	11	39	52	13
3	80	84	4	96	94	-2	45	68	23	41	55	14	45	53	8	5	9	4	85	95	10	5	10	5						
4	73	79	6	96	98	2	78	76	-2	67	100	33	47	57	10	21	30	9	71	83	12	10	0	-10	36	70	34	61	100	39
5	63	67	4	96	99	3	67	87	20	57	67	10	52	42	-10	7	0	-7							47	75	28	44	64	20
6								46			72		40	45	5	18	24	6	76	73	-3	5	0	-5	27	41	14	26	50	24
Mean	75	79	4	96	97	1	57	64	10	58	72	13	47	53	5	19	20	1	83	87	4	18	20	3	45	66	21	46	65	18
SD	7	7	1	0	2	2	19	19	11	15	15	14	5	7	8	14	15	7	10	10	6	21	31	12	14	14	10	15	21	16

The mean values of the correct answers of the questions in each round in Table 4 are computed from the individual c_j values of the universities using Equation (2).

$$\mu_c = \frac{1}{N} \sum_{j=1}^N c_j \quad (2)$$

The standard deviation (SD) is computed accordingly. Note that the mean value μ_c in Table 4 cannot generally be compared with a_i/n in Figure 1, even for questions with only one correct answer option since $\sum_i \sum_j \alpha_{ij} \geq n$.

3.4 Discussion of survey results

While the data show a general trend, they also show that replies to some questions are rather scattered. The effectiveness of the questions varied across the participating universities. For example, Question 4.2 (Slope angle) worked excellent at University 2 (see Figure 2). The correct answers of the students in the first round were 55% (within the range of 30% to 80%). The peer review (second round) led to an increase in correct answers up to 75%. In comparison, almost no student at University 3 chose the correct answer in the first round. No significant improvement was made due to the second round.

In the interview conducted after the quiz, the students gave empirical explanations for the distractors of Question 4.2 (Slope angle): For instance, the higher angle of repose was validated by experience on the beach, thus, confusing partially with fully saturated conditions. While the lower angle of repose was justified by an effect of seepage, the horizontal surface was explained by comparing the sand slipping under water to a *flowing material*.

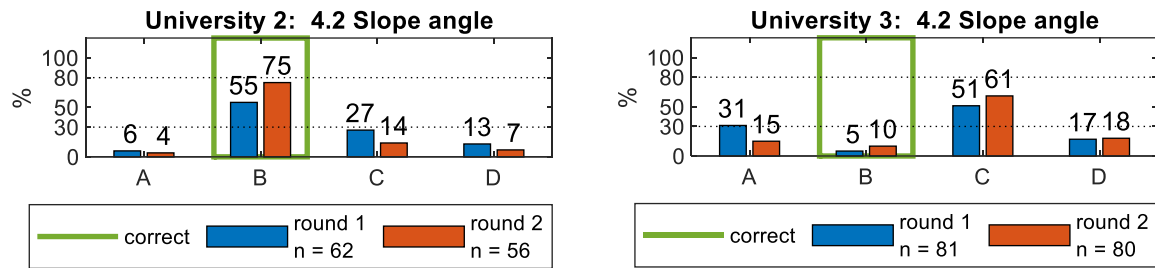


Figure 2. Example answers to Question 4.2 (Slope angle) for two universities

The mean values in Table 4 indicate that Questions 1.1, 2.1, 2.2, 3.1, 5.1, and 5.2 are suitable for peer instruction, whereas Questions 1.2 (Impact of compaction) and 4.1 (Soil shear strength) are too easy. Questions 3.2 (Foundation width effect) and 4.2 (Slope angle) can be considered as too difficult.

Specific answers that are hard for students to recognise as correct, e.g. the answer *Stiffness* in Question 1.1 (Impact of water), provide a good opportunity to talk about the stress dependence of stiffness and the effective stress concept, e.g. after the second round. This question was also widely debated within the *GeNIaL* network, without necessarily reaching a final conclusion, and highlights the challenges of creating questions for geotechnical concept inventories. It is evident that adding water alters the effective stress, which in turn affects the stiffness. However, one can argue that the change in effective stress is so minor that the change in stiffness can be considered negligible. This is another level of discussion, which is more related to modelling aspects in the general light of uncertainty of geotechnical parameters and not directly to mechanical concepts. As it is hard to distinguish between these two levels, it may be useful to skip the stiffness answer option in a concept inventory question. Nonetheless the option remains valuable to stimulate discussion in the classroom via a peer instruction setting. Another viewpoint is considering the term stiffness as the whole stress-strain relationship, which is the same with and without water. With that in mind, the answer option should then be changed from *Stiffness* to *Tangent stiffness*. Yet this leads to a further question regarding the definition of tangent stiffness.

Misconceptions can also be detected from Table 4, e.g. in Question 3.2 (Foundation width effect) the incorrect answer D (increasing settlements with decreasing foundation width at the same pressure) is often selected. This indicates a confusion between force and pressure. During the interviews (cf. Section 3.5) the students brought forward that a decreasing width with a constant *force* increases the pressure and, therefore, the settlement.

3.5 Students feedback and lecturers' observations

Students were asked to provide feedback after the second round or through conversations afterward. The feedback was gathered informally rather than through structured methods like questionnaires. Lecturers collected the feedback, added their own observations, and submitted it along with the results from the two rounds.

Thus, students confirmed for instance that the question formulation was generally clear and understandable to most. However, some issues arose with specific terminology. This is not seen as a problem with the questions themselves but rather with the students' familiarity with certain terms. Students further reported that some solutions were found by systematic elimination of wrong answers (e.g. Questions 2.1, 2.2, 3.1 and 3.2). Distractors and common misconceptions were described in Section 3.4.

Not all lecturers reported their observations for every question. Aside from some technical issues, some lecturers noted that students began discussing with each other already during the first round. It was also observed that students generally used the time well during the second round to exchange arguments. Even though there was hardly a trend for specific questions, typically Questions 1.1 and 1.2 sparked intensive discussions, while 2.1, 2.2, 3.1, 3.2, and 4.1 led to notable discussions. However, this varied strongly over the universities.

3.6 Further steps towards concept inventories for geotechnical engineering

Concept inventories (CIs) are instruments to assess students' knowledge of a specific set of fundamental concepts for a given subject. An inventory is usually a set of multiple-choice questions on a specific topic, each question with one (or more) correct answer(s) and several distractors, which cover typical misconceptions. From the outset, the authors aimed to develop such inventories for geotechnical engineering.

One of the first CIs was the *Force Concept Inventory* (Halloun & Hestenes, 1985; Hestenes et al., 1992). It was designed to assess students' understanding of the Newtonian concepts of force. While there are quite a few CIs and baseline tests for physics and mathematics (e.g. <https://www.physport.org/assessments/>), only a few inventories have been published for civil engineering education, e.g. the *Strength of Materials* CI by Richardson & Morgan (2001) or the *Statics* CI by Steif & Dantzer (2005). To the authors' knowledge there are no systematically developed CIs for geotechnical engineering.

The primary goal of a CI is not to obtain a summative assessment of student learning as in many conventional tests. Its purpose rather is to provide formative assessment of teaching. As stated by Adams & Wieman (2010) "the results from the students as a group are more important than ranking individual students, which is fundamentally different from many other assessments". By means of CIs it is possible to uncover and address bottlenecks in the students' conceptual understanding already during the teaching process. Adams & Wieman (2010) describe in detail how to develop such inventories as Formative Assessments of Instruction (FASI). They recommend to follow a structured, iterative process to ensure validity and reliability of the individual questions.

While initial phases of test development focus on defining scope and specifications, it is then crucial to create, refine and validate the test instrument by means of the following steps:

- Identify key topics valued by educators.
- Conduct student interviews to explore how their thinking diverges from expert reasoning.
- Develop open-ended survey questions to capture a broad range of student understanding.
- Convert these into multiple-choice or Likert-scale questions for standardisation.
- Validate questions through expert and student interviews.
- Administer the test, analyse statistical reliability, and refine questions accordingly.

In a last phase, the test is finalised for operational use. This includes structuring the assessment, validating its effectiveness across institutions, and ensuring it accurately measures instructional impact. Continuous validation and refinement ensure meaningful insights for improving teaching and learning.

The work done by the authors in their *GeNIaL* network covers some steps of the above summarised process. The initial survey results have been collected. These findings help guide the next steps, allowing for refinement and review of the developed questions with experts and students.

In the authors' opinion, CIs offer a range of benefits in the long term, both in educational practice and broader academic strategy. At their core, they encourage educators and experts to define and reflect upon the essential disciplinary concepts and competencies that should form the foundation of their teaching. This process helps establish clear and focused learning objectives for courses in geotechnical engineering and tailor educational methods and materials accordingly. Furthermore, the design of the questions makes them valuable FASI tools for both pre- and post-course evaluations.

Beyond individual courses, CIs could facilitate coordinated consensus-building within the teaching community, institutional committees and professional associations. This collaboration helps support and enhance relevant teaching activities.

4 Concluding remarks

The study emphasises the importance of defining and assessing core competencies in geotechnical engineering education, e.g. by introducing concept inventories as a means of formative assessment. The *GeNiaL* teaching network has developed a structured approach to identify essential geotechnical skills and formulate corresponding learning outcomes.

The survey, conducted at six universities using a peer teaching concept, revealed varying levels of student understanding. While certain concepts are well understood, misconceptions persist in areas such as soil stiffness and foundation width effects. The peer teaching method proved effective in testing conceptual understanding. However, some questions were found to be either too easy or too difficult, requiring further refinement.

Following the structured approach provided, future work should focus on refining the test questions, developing concept inventories, and presenting them to a wider geotechnical academic community. Standardised assessment tools should be integrated into engineering curricula to improve geotechnical education across universities.

Acknowledgements

Support and fruitful exchange within the *GeNiaL* teaching network are gratefully acknowledged. The authors thank Karsten Dörendahl, Katharina Kluge, Kerstin Lesny, Mona Siahkouhi, and Lukas Wimmer for performing the survey in their lectures in addition to the authors' own surveys. Moreover, Peter Riegler provided useful thoughts on concept inventories in general.

The authors declare the use of *ChatGPT* for drafting the abstract and conclusion of this publication. It was furthermore used together with *DeepL* for shaping the writing.

References

- Adams, W. K., Wieman, C. E. (2010). Development and validation of instruments to measure learning of expert-like thinking. *International journal of science education*, 33(9), pp. 1289-1312.
- ASBau - Accreditation Association for Study Programmes in Civil Engineering e.V. (2021), Reference Framework for Civil Engineering Courses (Bachelor). https://www.asbau.org/assets/dl/ASBau_RR_2021_dl.pdf
- Atkinson, J. (2008). What should geotechnical engineers be able to do and how should they acquire these skills? *Proceedings of the 1st International Conference on Education and Training in the Geo-sciences*, Constantza, Romania, June 2-4, Manoliu & Radulescu (eds.), pp. 1-8, Taylor & Francis, London.
- Atkinson, J. (2012). What should geotechnical professionals be able to do? *Proceedings of the International Conference Shaking the Foundations of Geo-engineering Education SFGE 2012*, Galway, Ireland, July 4-6, McCabe, Pantazidou & Phillips (eds.), pp. 3-7, Taylor & Francis, London.
- Atkinson, J. (2016). First John Burland Lecture: Basic Geotechnical Engineering Skills - What Can Graduates Do? *ISSMGE Int. Conf. Shaping the Future of Geotechnical Education SFGE 2016*, Belo Horizonte, Brazil, Oct. 19-20, <https://www.issmge.org/education/videotaped-honor-lectures/first-john-burland-lecture>, (accessed 25 Dec. 2024).
- Baldwin, M. J. (2012). Key skill sets for use in geotechnics – a contractor's view. *Proceedings of the International Conference Shaking the Foundations of Geo-engineering Education SFGE 2012*, Galway, Ireland, July 4-6, McCabe, Pantazidou & Phillips (eds.), pp. 47-52, Taylor & Francis, London.
- Bloom, B. S., Engelhart, M. D., Furst, E. J., Hill, W. H., Krathwohl, D. R. (1956). *Taxonomy of educational objectives: The classification of educational goals. Vol. Handbook I: Cognitive domain*. New York: David McKay Company.
- Crouch, C. H. (1998). Peer instruction: An Interactive Approach for Large Lecture Classes. *Optics and Photonics News*, 9(9), pp. 37-41. <https://doi.org/10.1364/OPN.9.9.000037>
- Crouch, C. H., Mazur, E. (2001). Peer Instruction: Ten years of experience and results. *American Journal of Physics*, 69(9), pp. 970-977. <https://doi.org/10.1119/1.1374249>

- Fagen, A. P., Crouch, C. H., Mazur, E. (2002). Peer Instruction: Results from a Range of Classrooms. *The Physics Teacher*, 40(4), pp. 206-209. <https://doi.org/10.1119/1.1474140>
- Fiegel, G. L. (2012). Will this be on the final exam? Learning objectives for an introductory geotechnical engineering course. *Proceedings of the International Conference Shaking the Foundations of Geo-engineering Education SFGE 2012*, Galway, Ireland, July 4-6, McCabe, Pantazidou & Phillips (eds.), pp. 53-59, Taylor & Francis, London.
- Halloun, I. A., Hestenes, D. (1985): Common sense concepts about motion. *American Journal of Physics*, 53(11), pp. 1056-1065.
- Hestenes, D., Wells, M., Swackhamer, G. (1992). Force concept inventory. *The Physics Teacher*, 30(3), pp. 141-158.
- Kluge, K., Kirsch, A., Budach, C. (2023): Digitale Lehre in der Geotechnik: Aktueller Stand und weitere Entwicklungen (Digital teaching in geotechnical engineering: current state of the art and future developments), *geotechnik*, 46(1), pp. 48-55. <https://doi.org/10.1002/gete.202200013>
- Lees, A. S. (2015). A competency based approach to managing skills in geotechnical numerical analysis, *Proceedings of the XVI ECSMGE*, Edinburgh Sept. 13-17, *Geotechnical Engineering for Infrastructure and Development*, pp. 4283-4287.
- Matos Fernandes, M. Couto Marques, J. (2020). Highlighting Links among Geology, Index Properties and Mechanical Behaviour at the Beginning of a First Course in Soil Mechanics, *Proceedings of the International Conference on Geotechnical Engineering Education 2020 (GEE2020)*, Pantazidou, Calvello & Pinho Lopes (eds.), obtained from <https://www.issmge.org/publications/online-library>.
- Mazur, E. (1997). *Peer Instruction: A User's Manual*, Prentice Hall, Upper Saddle River, NJ.
- Richardson, J., Morgan, J. (2001). Development of an Engineering Strength of Material Concept Inventory Assessment Instrument, *Proceedings of the Frontiers in Education Conference*, Reno, Nevada, 10-13 Oct.
- Pantazidou, M. (2016). Bridging Geotechnical Engineering Education and Research on Education, *Proceedings of Int. Conf. Shaping the Future of Geotechnical Education*, SFGE 2016, Belo Horizonte, Brazil, Oct. 20-21, obtained from <https://www.issmge.org/publications/online-library>.
- Pantazidou, M. (2020). Teaching the Big Ideas of the Disciplines: Online Educational Material Accessible to Everyone for Soil Mechanics' Effective Stress, *Proceedings of the International Conference on Geotechnical Engineering Education 2020 (GEE2020)*, Pantazidou, Calvello & Pinho Lopes (eds.), obtained from <https://www.issmge.org/publications/online-library>.
- Phillips, D. T. (2020). A Study Evaluating Students' Long term Understanding of Effective Stress and Suggestions for its Improvement. *Proceedings of the International Conference on Geotechnical Engineering Education 2020 (GEE2020)*, Pantazidou, Calvello & Pinho Lopes (eds.), obtained from <https://www.issmge.org/publications/online-library>.
- Phillips, D. T., McCabe, B. A. (2008). Launching Geotechnical Education into the 21st Century. *Proceedings of the 1st International Conference on Education and Training in the Geo-sciences*, Constantza, Romania, June 2-4, Manoliu & Radulescu (eds.), pp. 439-442, Taylor & Francis, London.
- Schofield A. (2016). 24rd Prague Geotechnical lecture: Critical States of Soil and Geotechnical Centrifuge Tests. *Prague geotechnical days*, 9.-10. May 2016.
- Shidlovskaya, A., Briaud, J.-L. (2016). Modern syllabus for introduction to geotechnical engineering. *Proceedings of Int. Conf. Shaping the Future of Geotechnical Education*, SFGE 2016, Belo Horizonte, Brazil, Oct. 20-21, obtained from <https://www.issmge.org/publications/online-library>.
- Steif, P.S., Dantzler, J.A. (2005). A statics concept inventory: Development and psychometric analysis, *Journal of Engineering Education*, 94(4), pp. 363-371. <https://doi.org/10.1002/j.2168-9830.2005.tb00864.x>
- Technische Hochschule Augsburg (online). Peer Instruction. <https://www.tha.de/Peer-Instruction.html>, (in English and German; accessed 25 Jan. 2025).

Authors' bios

Ansgar Kirsch, University of Applied Sciences Aachen (Germany)

Dr. Ansgar Kirsch has been a full professor of geotechnical engineering at the University of Applied Sciences in Aachen (www.fh-aachen.de) responsible for teaching soil mechanics and (under)ground engineering since 2015. He holds a civil engineering diploma from RWTH Aachen (2004) and an International Diploma from Imperial College London (2002). He earned his PhD from the University of Innsbruck, Austria, (2008) and worked at ILF Consulting Engineers in Innsbruck (2010–2015) before transitioning to academia.

Passionate about teaching and student engagement, he has served as vice-dean for teaching since 2018 and contributes to various university boards on higher education. As member of the national teaching network *Lehre^n* and co-founder of the *GeNIaL* network, he actively promotes digital and interactive learning. His commitment to educational innovation has been recognised through multiple awards, including the 2018 Fellowship for Digital Higher Education in North Rhine-Westphalia and his university's teaching award in 2022. His expertise includes: inverted classroom, interactive online tools and STACK programming.

Wolfgang Fellin, University of Innsbruck (Austria)

Dr. Wolfgang Fellin is an associate professor at the University of Innsbruck (www.uibk.ac.at) who specializes in the field of Geotechnical Engineering. He holds his Civil Engineering degree from University of Innsbruck. His interdisciplinary research interests include material modelling of soils and natural hazards like snow avalanches and large mass movements. Dr. Fellin was the first to use flipped teaching at his faculty more than 20 years ago and investigated the effect of various teaching measurements in a scientific way. In 2013, he was awarded with the prize for excellence in teaching at public universities in Austria. He achieved the OER Practitioner certificate in 2024.



René Sonnenberg, Magdeburg-Stendal University of Applied Sciences (Germany)

Dr. René Sonnenberg has been a full professor at Magdeburg-Stendal University of Applied Sciences (www.h2.de) since 2019. He teaches Fundamentals of Civil Engineering and Geotechnics at both, the undergraduate courses and master's courses.

He studied Civil Engineering at the Bauhaus-Universität Weimar (Germany) and earned his PhD from the University of Dundee (Scotland). His professional experience includes working as a senior geotechnical engineer abroad, notably in New Zealand and in Russia. Before transitioning to academia, he worked for Deutsche Bahn (the German Railway).

Passionate about hands-on learning, Dr. Sonnenberg integrates classroom experiments into his teaching and was nominated Best Teacher of the Year in 2023 by his students.

Enhancing student learning in geotechnical engineering: a study on effective slide design from students' perspective

V. Mangraviti, L. Brezzi, G. Dalla Santa, F. Gabrieli & F. Ceccato

University of Padua, Padua, Italy

viviana.mangraviti@unipd.it, lorenzo.brezzi@unipd.it, giorgia.dallasanta@unipd.it,
fabio.gabrieli@unipd.it, francesca.ceccato.1@unipd.it

ABSTRACT: This paper explores the effectiveness of slides in teaching STEM subjects, particularly geotechnics. While slides are crucial for explaining basic concepts, some can be challenging for both teachers to explain and students to grasp. The study acknowledges that teachers often have favourite images they believe effectively convey key concepts in soil mechanics or geotechnical engineering. However, due to differences in age and learning stage, students may not find these slides as clear or meaningful. The research comprised two parallel surveys: one student-based and one teacher-based, to examine the preferred slide styles for fundamental geotechnical concepts and the motivations. Key geotechnical topics (shear resistance and drained/undrained conditions) were presented using two different slide styles. Using the Wooclap platform, surveys were conducted during lessons with about 80 students from diverse backgrounds in both undergraduate and advanced geotechnics courses. Students were asked to choose their preferred slide and explain their choice. The same was asked to teachers through Google Forms. This study aims to understand students' perspectives on the use of figures in geotechnical engineering slides, potentially serving as a reference for lecturers. The preliminary results have enabled the authors to develop a list of tips for teachers on presenting difficult-to-visualize topics in geotechnics more effectively.

Keywords: Slide design, Smart learning, Student-based

1 Introduction

Teaching has evolved in recent years through the experimentation of new student-teacher interaction methods and technological advancements that have introduced new tools and multimedia aids into classrooms. Regarding this second aspect, particularly in Science, Technology, Engineering and Mathematics (STEM) fields, traditional "chalk-and-talk" lectures have gradually been replaced, first by the use of overhead projector transparencies (OHP) and later by PowerPoint presentations (slideware).

In this evolutionary process, not only has the graphical medium changed (i.e., from analogue to digital), but also the type, quality, and quantity of information conveyed, which have adapted to the new possibilities offered by these tools. Previously, the teacher's spoken explanation was predominant over drawings and diagrams (with more complex figures relegated to textbook readings or handouts distributed in class). Now, however, the graphical component has become increasingly present in PowerPoint slides, incorporating coloured text and objects, static drawings, and photographs, as well as videos and animations.

Throughout this transformation, many researchers have questioned whether and how these tools can be more effective in knowledge transmission. Harknett & Cobane (1997) and Daniels (1999), referring to Information Communication and Technology (ICT) related courses, highlighted the potential of PowerPoint presentations in terms of speech organization, readability of information, and the ability to make lectures more interactive and engaging through animations, as well as the ease with which they can be updated by the teacher.

However, the effectiveness of slideware compared to OHP and blackboard lectures remains uncertain and debated. Study results sometimes favour the use of PowerPoint (Szabo & Hastings, 2000), while other studies find no significant differences (Ahmed, 1998), and some even report negative outcomes (Savoy et al., 2009). As Yilmazel-Sahin (2009) points out, estimating the effectiveness of PowerPoint presentations is challenging due to the variability in styles, content, and contexts, which in turn depend on the individual creating them.

When evaluating effectiveness, it is always important to distinguish between the opinions of teachers and those of students (MacKiewicz, 2008), as well as what comes from students' academic performance (Bartsch and Cobern, 2003). For example, Savoy et al. (2009) measured a 15% decrease in the amount of verbally delivered information retained by students when accompanied by PowerPoint presentations, despite students expressing a preference for PowerPoint over traditional presentations and spoken lectures. In this sense, slides may act as a distraction from the spoken content, especially when there is no clear connection between the two. Masie (2006) argues that many PowerPoint presentations can negatively impact teaching methods, as teachers may tend to present disconnected lists of concepts rather than integrating them into a coherent narrative, which in turn may reduce students' interest in the subject.

Regarding presentation style and content, several studies exist across both STEM and humanities-psychology fields (Johnson & Christensen, J., 2011; Kernbach et al., 2015). Apperson et al. (2008), for instance, conducted a survey on a cohort of psychology students and found that they preferred slides containing key phrases that the teacher then elaborates upon verbally, keeping them actively engaged in the learning process. Similarly, videos can serve as learning prompts if used in a targeted manner (Bartsch & Cobern, 2003). Students also reported a preference for light-coloured backgrounds and suggested dimming the lights during presentations to enhance screen visibility without making it difficult to see their notes or maintain eye contact with the teacher. Additionally, they expressed a preference for receiving slides as handouts. Tangen et al. (2011) found that students performed better when exposed to graphics-rich presentations compared to traditional bullet-point PowerPoint slides. Other authors reached the same conclusions in pilot studies with geology students (Alley et al., 2005) and engineering students (Garner & Alley, 2016), comparing text-only slides (using bullet points) with slides where sentences were supported by graphics. The latter type ("assertion-evidence" style) was preferred by students, who also achieved better performance in quizzes. The criticism that could be raised against this type of comparison is that the text-only slides used by the authors, while containing the necessary information, are text-heavy and stylistically very poor.

According to the Cognitive Theory of Multimedia Learning (CTML), learning occurs simultaneously through a verbal channel (for text and narration) and a non-verbal channel (for images and animations). To maximize efficiency, presentations should leverage and carefully structure both channels (Mayer, 2021). Moreover, the audience must be able to absorb information in an organized manner - neither too much at once nor excessively fragmented (limited capacity assumption) - so they can select, organize, and integrate it effectively (active learner assumption). Cavanagh (2023) suggests that, regarding content and style, presentations should follow the principles of proximity, alignment, repetition, and contrast to create visual slide structures that align with the underlying conceptual framework of the presented information.

As a STEM discipline, geotechnical engineering requires presentations that balance textual content, graphics, and spoken explanations. In this context, an important question arises: what is the most effective strategy for conveying key geotechnical concepts, particularly concerning stylistic aspects? To the authors' knowledge, no specific studies have examined these stylistic aspects in geotechnical education.

This study presents the results of a survey conducted on approximately eighty students and twenty teachers, evaluating preferences for two types of presentations on two classic geotechnical topics: soil shear strength and shear behaviour in drained/undrained conditions. These findings aim to offer valuable insights into students' and teachers' preferences for visual presentation of fundamental geotechnical concepts, which could inform future approaches to educational material design in the geotechnical field.

2 Methodology

The authors of this paper prepared two slides with different styles on two fundamental topics of soil mechanics, i.e. shear strength of soils in drained conditions and soil response in drained/undrained conditions. One slide is prepared with a textbook-like style, meaning that there is a long text explaining the content and a black and white figure. Figure 1 and Figure 2 show the slides used for talking about shear strength and drained/undrained conditions respectively. The other is a presentation-like slide with only a few words, more colourful, and with simple figures to remind key definitions. Figure 3 and Figure 4 show the slides we used for this case. Good quality slides can be downloaded here: <https://researchdata.cab.unipd.it/id/eprint/1497>.

Shear conditions

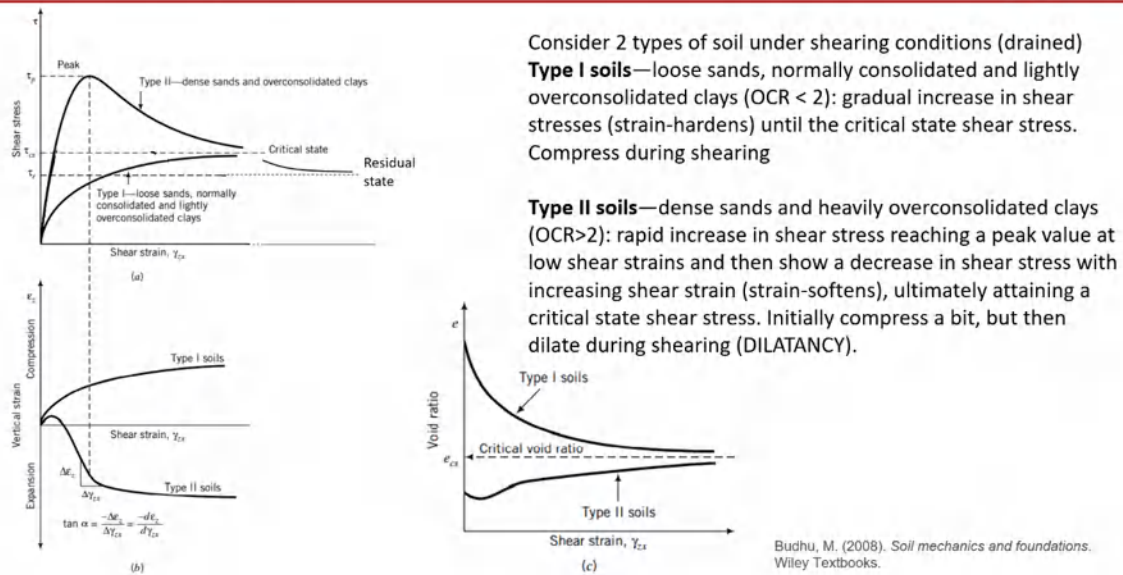


Figure 1. Textbook-like slide style for shear behaviour of soil in drained conditions

Undrained conditions



- Drained condition occurs when the excess pore water pressure developed during loading of a soil dissipates, i.e., $\Delta u = 0$. (typical of sand, and clay at long term)
- Undrained condition occurs when the excess pore water pressure cannot drain, at least quickly, from the soil, $\Delta u \neq 0$. (typical of clay at short term)

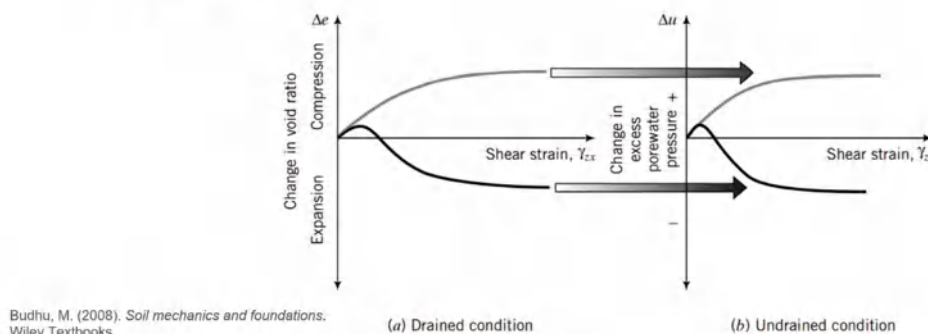


Figure 2. Textbook-like slide style for drained and undrained conditions

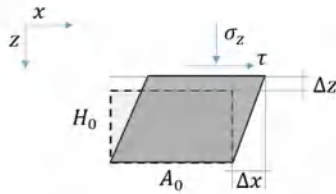
The textbook-like slide can be prepared very easily re-using, with permission, figures and text from a soil mechanics book, requiring limited effort for the teacher. During the lesson the teacher can read the text and add additional explanations and content to enrich the slide. The presentation-like slide requires

more effort both to prepare graphs and drawings using Power-Point and to explain the content during the lesson, i.e. the teacher will explain the topic describing the figures, whereas the text is only used to highlight key concepts.

Shear conditions



Shear deformation of soil:



$$\gamma_{zx} = \frac{\Delta x}{H_0} \quad \text{Shear strain}$$

$$\varepsilon_v = \frac{\Delta V}{V_0} = \frac{A_0 \Delta z}{A_0 H_0} = \frac{\Delta z}{H_0} \quad \text{Volumetric strain (compression is positive)}$$

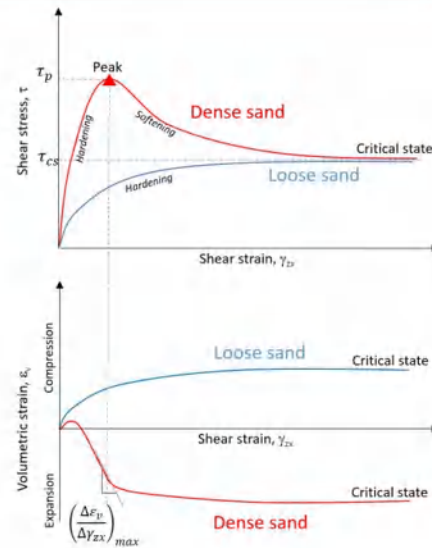


Figure 3. Presentation-like slide for shear behaviour of soil in drained conditions

Undrained conditions

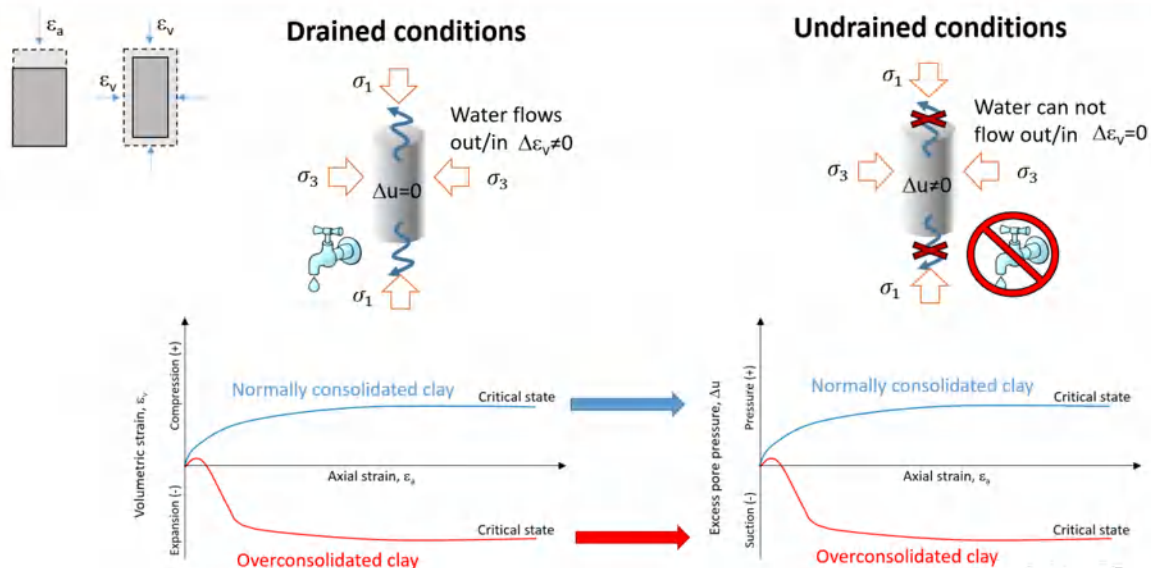


Figure 4. Presentation-like slide for drained and undrained conditions

For the purpose of this study, the two slides of the same topic were shown one after the other to the students without additional explanations by the teacher, who then asked, “what slide do you prefer?” (2 alternative options) and “why?” (short text answer). Replies were collected using Wooclap, an on-line interactive questioning platform.

From the analysis of the short text answers, the reasons why the prefer one type of slide with respect to the other were grouped in five classes from the authors:

1. Comprehensive information through more writing: a group of students felt that in textbook-like slide more text made the content more complete and easier to understand, reducing dependence on the teacher's teaching style.

2. More writing for at-home study: some students preferred text-heavy slides for independent study, expressing a written desire for the teacher's interpretation of plots and diagrams.
3. Less writing for in-class engagement: some students preferred slides with less text (presentation-style slide) during lectures, citing increased incentive to listen and more space for notetaking on the slide.
4. Preference for colourful/intuitive graphics: students favoured slides with visually appealing and easy-to-understand graphics (presentation-style slide).
5. Clarity through less writing: a portion of students found that less text made the slides clearer and more schematic, which they considered beneficial for revision purposes (presentation-style slide).

Replies from students of the University of Padua (Italy) were collected during the first semester of the academic year 2024/2025. A part of them (about 40%) are students from master's degree (graduate students, GS) in Civil Engineering and Water and Geological Risk Engineering (<https://www.dicea.unipd.it/corsi-di-studio>) and the slides have been shown during a lesson dedicated to a recap of soil mechanics. The slides were first shown to students asking to recall in their mind the concepts and then the teacher lead the recap. These students followed the course of geotechnics a few years earlier, but these topics may not be fresh in their minds.

The remaining (about 60%) are bachelor students (undergraduate students, US) in Civil Engineering (<https://www.dicea.unipd.it/IC>), following the course of geotechnics for the first time, and they received a detailed theoretical explanation on the topic a few days earlier, using different slides. In this case, the surveyed slides were both briefly explained by the teacher, to recap the principles learned before. After the presentation, the students were surveyed.

To minimize potential bias in student responses, the order of slide presentation was varied across topics for both groups of students. For the first topic, the presentation-like slide was shown before the textbook-like slide, while this order was reversed for the second topic. The specific sequence of slide presentation was as follows: Figure 3, Figure 1, Figure 2, and Figure 4.

In the following, the answers of the two groups of students are processed separately.

The same questions were posed to geotechnical teachers in Italy by contacting them via e-mail and asking to fill a Google Form (in Italian). 21 teachers of different age (from 31 to 70) replied to the survey. We asked them which of the two slides they prefer to use for one of their geotechnical classes and why. The motivations can be chosen between the following options, but they can also suggest alternative answers:

- 1) If they prefer the presentation-like slide:
 - a) Fewer words make the slide clearer/more schematic.
 - b) Fewer words help the student review at home.
 - c) Fewer words are more useful in class, the student focuses on what I'm saying.
 - d) With lots of text, the student is encouraged to get distracted from my explanations while reading the slides.
 - e) Few words so the student can take notes directly on the slides.
 - f) Few words "force" the student to attend class.
 - g) Few words require the student to pay attention to explanations in the classroom.
 - h) Few words so the student is 100% focused on my words.
 - i) Drawings help the student internalize concepts better than words.
- 2) If they prefer the textbook-like style:
 - a) Lots of text helps the student study at home.
 - b) Content in the slides helps the student if they are absent from class.
 - c) Written concepts make the explanation more complete and easier to understand.
 - d) Lots of text helps me as a teacher to cover all the important things in the lesson.
 - e) Better to prefer text and avoid colourful drawings that distract.
 - f) Lots of text so the student doesn't feel obligated to take notes and can concentrate on my words.
 - g) Lots of text because it's better to be redundant between oral explanation and written concepts (repetition helps).
 - h) Words help the student internalize concepts better than diagrams and drawings.

For the following elaboration of the results these answers are grouped into 6 classes:

1. Comprehensive information through more writing: 2c, 2d, 2g.
2. More writing for at-home study: 2a, 2b.
3. Less writing for in-class engagement: 1c, 1d, 1e, 1f, 1g, 1h.

4. Preference for colourful/intuitive graphics: 1i.
5. Clarity through less writing: 1a, 1b
6. More writing for clarity and in-class engagement: 2e, 2f, 2h.

3 Results and discussion

In this section the data regarding student and teachers' preferences for different slide styles are examined. The two key topics evaluated are indicated in the graphs as "shear strength" (Figure 1 and 3), and "drained/undrained conditions" (Figure 2 and 4).

For the shear strength topic, a total of 80 responses were collected (52 US and 28 GS). The survey asked students to indicate their preferred slide style for presenting this concept and revealed that 32 students (40% of the total population) preferred the presentation-like style and 48 of them (60%) preferred the textbook-like style for this concept. Notably, this preference is not equally distributed across the two groups, with 18 undergraduate students (35% among the US, see Figure 5.a) and 14 graduate students (50% among the GS, see Figure 5.c) selecting the presentation-like. These findings indicate a clear preference among undergraduate students for the textbook-like style when learning about shear strength. The great majority (65%) of undergraduates favoured this approach, suggesting that for this topic, they find more detailed, text-heavy slides beneficial. In contrast, graduate students showed no clear preference between the two styles for this topic. The even split (50% for each style) among graduate students might indicate greater adaptability to different presentation formats or a more diverse set of learning preferences at this academic level, highlighting the importance of considering the target audience when designing educational materials. While undergraduate students seem to benefit from more comprehensive, textbook-like presentations for topics like shear strength, graduate students appear equally comfortable with both detailed and more schematic presentation styles.

Regarding the drained/undrained conditions topic, 75 responses were obtained (41 US and 34 GS). The slight difference in response rates between the two questions (80 vs. 75) is because the two topics were presented in different days. Students were again asked to select their preferred slide style for this concept and 40 students (53% of the total) favoured the presentation-like style, while 35 students (47%) preferred the textbook-like style. In detail, 18 undergraduate students (44% among the US, see Figure 5.b), and 22 graduate students (35% of the GS, Figure 5.d) preferred the presentation-like style for this topic. This preference may be attributed to the inclusion of visual representations of the sample and sink in the presentation-like slide (Figure 4), elements which were absent in the textbook-like version (Figure 2).

Beyond preference, students were asked to provide motivation for their choices (Figure 6). Most of US, having more writing was more useful for having comprehensive information, whereas for GS less writing is more important for clarity. This may be due to GS' more extensive knowledge on the topics and their higher visual literacy and ability in taking notes.

It should be considered that there are possible biases in reading these results, the effect of which is difficult to assess. Specifically, (i) the culture of teaching at the University of Padua, as most people are more comfortable with what they are used to; (ii) whether students read the textbook before class; (iii) cultural differences among students.

In addition to surveying students, the same questions were posed to teachers to evaluate their preferences and compare them with those of students. The results revealed a notable contrast in approach and motivation. Teachers demonstrated a remarkably consistent preference in their slide style choices. Unlike the diverse opinions observed among students, 86% of the surveyed teachers (18 out of 21) expressed a clear preference for the presentation-like style (Figure 7a,b). Their primary motivation for this choice was focused on capturing and maintaining student attention during class sessions. Teachers aim to push students to pay attention and interpret the figures while they are being discussed in class by taking notes, to actively involve them in the cognitive process.

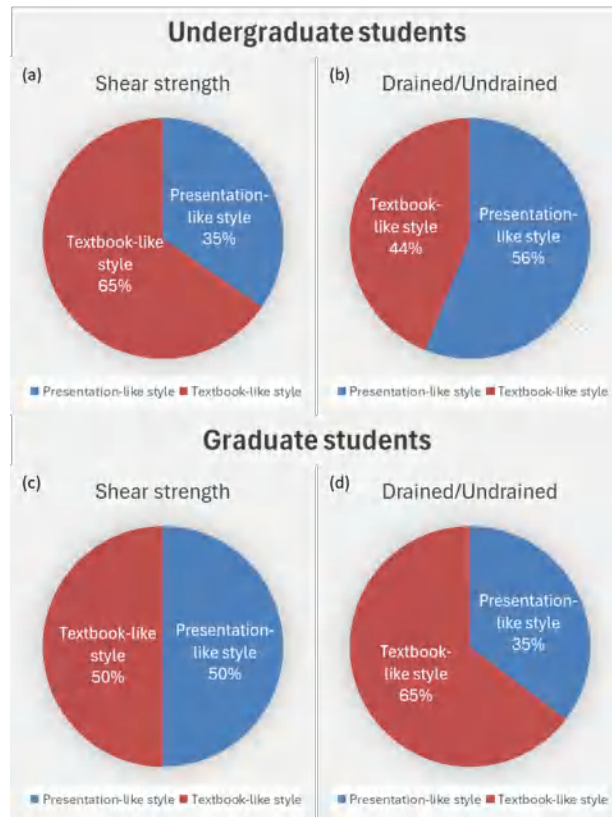


Figure 5. Preferences for slide style from: undergraduate students on (a) shear strength and (b) drained/undrained; and graduate students on (c) shear strength and (d) drained/undrained topics

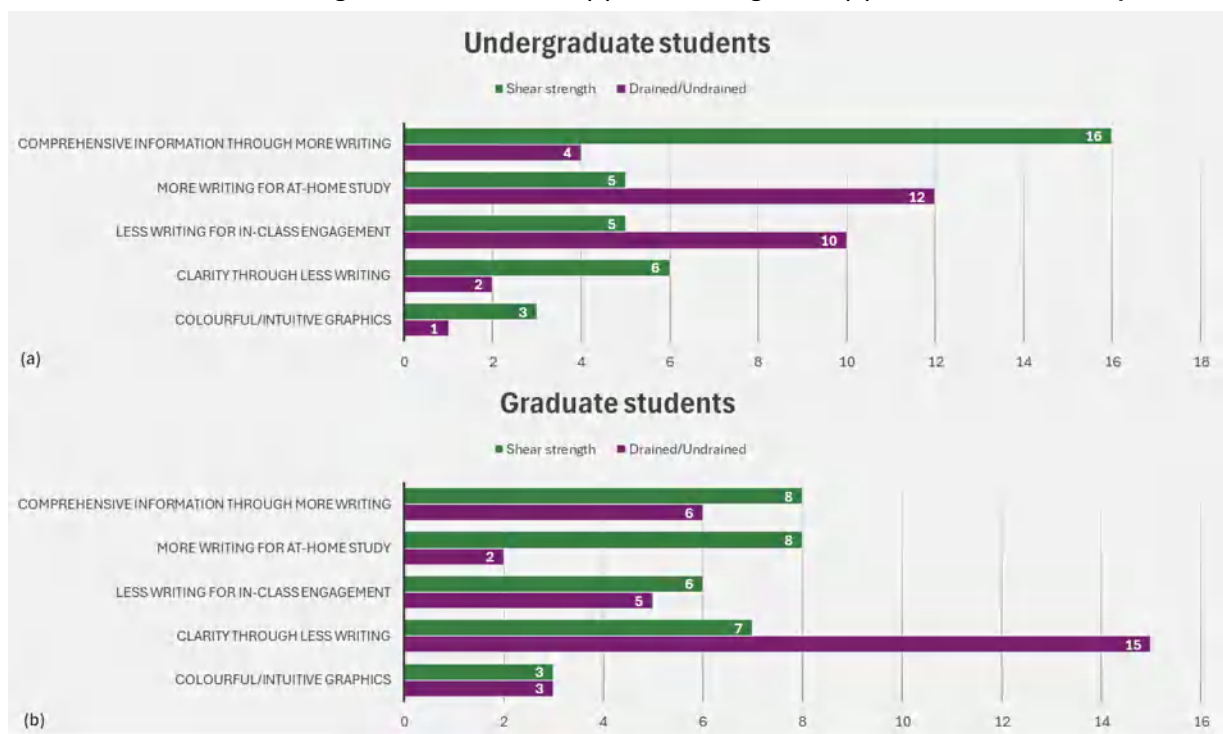


Figure 6. Number of students grouped for motivation for shear strength and drained/undrained topics: (a) undergraduate students; (b) graduate students

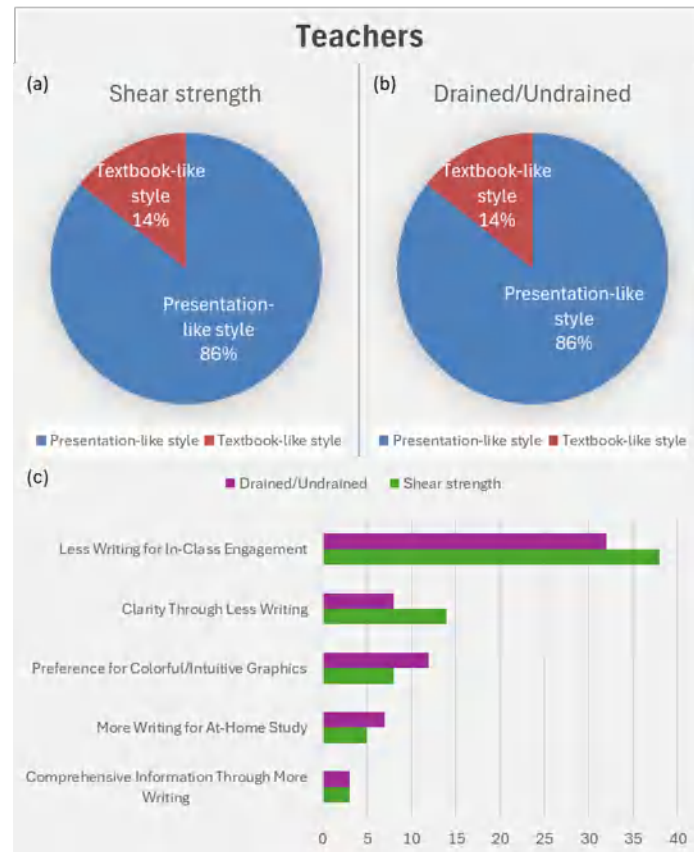


Figure 7. Teachers' preferences for slide style for (a) shear strength and (b) drained/undrained topic. (c) Number of teachers grouped for motivation

In Figure 7c the comments made by teachers have been categorized into the six main categories (see Sec. 2). The last category (More writing for clarity and in-class engagement) was not selected by anyone, so it is missing from the figure. It is important to note that the total number of comments exceeds the number of teachers surveyed because each participant had the opportunity to express multiple preferences or provide several comments related to the same category.

Also, the results from teachers might have biases difficult to quantify, such as the teaching experience, personality, and cultural background.

This uniformity in teacher preferences stands in stark contrast to the more varied preferences observed among students. While students' preferences fluctuated based on factors such as academic level and specific topic (depending on their previous personal knowledge; their ability in writing notes during lessons and their personal study methodology), teachers consistently prioritized engagement and attention-grabbing elements in their slide design choices. This alignment of all teachers towards the presentation-like style may not fully address the diverse learning preferences expressed by students, particularly undergraduates who often favoured more detailed, textbook-like slides for certain topics.

Possible causes of textbook-like style preference among students may lay on:

- the fact that, with this type of slide, the influence of the teacher's ability in explaining the proposed concept and catching the audience is less important.
- students' and teachers' ability to understand graphs and figures can be very different. Usually, teachers have higher visual literacy (Christidou, 2020). The slides without written parts make the graphs/images central to the lesson and the student may not feel able to fully understand the concept.

Only few teachers preferred textbook-like slides, and the main reason is that text can better support the home study, providing the most important concepts to acquire. In addition, textbook-like slides can be very useful in conveying the subject proper language, in particular, in case there is not a reference textbook for self-study at home.

4 Conclusions

This study presented the results of a survey conducted on both students and teachers to investigate their preferences in slide styles for two classic geotechnical topics: soil shear strength and drained/undrained conditions. Even though the sample sizes for both questions are substantial (80-75 students and 21 teachers), to provide a more robust basis for analysis, larger samples should be considered.

The findings showed that depending on the topic presented and their academic level, students tend to prefer textbook-like style, whereas teachers are less likely to put a lot of text on slides. The divergence between teacher and student preferences highlights an important consideration in educational material design. While teachers prioritize in-class engagement, students' preferences often reflect their needs for both in-class learning and independent study. This difference underscores the challenge of creating educational materials that balance immediate classroom engagement with comprehensive content for later review and study.

In conclusion, few tips for teachers preparing PowerPoint slides for geotechnical topics can be derived from this study.

- 1) Thinking about the scope of the material you are preparing:
 - a) Are the slides replacing a textbook?
 - b) Are the slides made to take notes on them?
- 2) Think about background and abilities of the audience:
 - a) What is the academic level?
 - b) What could be their visual literacy?

The key is perhaps to balance written text, graphics, images, and narration without being too concise in the text (as teachers would prefer) or, on the other hand, too verbose (as students might desire).

The findings offered a valuable insight into student and teachers' preferences for visual presentation of complex geotechnical concepts, which could inform future approaches to educational material design in the geotechnical field.

References

- Alley, M., Schreiber, M., Muffo, J. (2005). Pilot testing of a new design for presentation slides to teach science and engineering. *Proceedings Frontiers in Education 35th Annual Conference*, pp. S3G-7. IEEE, Indianapolis, IN, USA. <https://doi.ieeecomputersociety.org/10.1109/FIE.2005.1612283>
- Apperson, J. M., Laws, E. L., Scepansky, J. A. (2008). An assessment of student preferences for PowerPoint presentation structure in undergraduate courses. *Computers & Education*, 50(1), pp. 148-153. <https://doi.org/10.1016/j.compedu.2006.04.003>
- Bartsch, R. A., Cobern, K. M. (2003). Effectiveness of PowerPoint presentations in lectures. *Computers & education*, 41(1), pp. 77-86. [https://doi.org/10.1016/S0360-1315\(03\)00027-7](https://doi.org/10.1016/S0360-1315(03)00027-7)
- Cavanagh, T. (2023). Cognitive and Graphic Design Principles for Creating Well-Organized, Visually Appealing Slide Decks. *Business and Professional Communication Quarterly*, 86(1), pp. 33-51. <https://doi.org/10.1177/23294906221131988>
- Christidou, V. (2020). When Graphs are More than 'Pictures': Visual Literacy as a Challenge for STEM education. *Proceedings of the 5th International Conference on Geotechnical Engineering Education*, Pantazidou, M., Calvelo, M., Pinho Lopes, M. (Eds.), pp. 26-37, ISSMGE, Athens, Greece.
- Daniels, L. (1999). Introducing technology in the classroom: PowerPoint as a first step. *Journal of Computing in Higher Education*, 10, pp. 42-56. <https://doi.org/10.1007/BF02948722>
- Garner J. K., Alley M. P. (2016). Slide structure can influence the presenter's understanding of the presentation's content. *International Journal of Engineering Education*, 32(1), pp. 39–54. <https://doi.org/10.18260/1-2--19685>
- Harknett RJ, Cobane CT. (1997). Introducing Instructional Technology to International Relations. *PS: Political Science & Politics*, 30(3), pp. 496-500. doi:10.2307/420130
- Johnson, D. A., Christensen, J. (2011). A Comparison of Simplified-Visually Rich and Traditional Presentation Styles. *Teaching of Psychology*, 38(4), pp. 293-297. <https://doi.org/10.1177/0098628311421333>

- Kernbach, S., Bresciani, S., Eppler, M. J. (2015). Slip-Sliding-Away: A Review of the Literature on the Constraining Qualities of PowerPoint. *Business and Professional Communication Quarterly*, 78(3), pp. 292-313. <https://doi.org/10.1177/2329490615595499>
- MacKiewicz, J. (2008). Comparing Powerpoint Experts' and University Students' Opinions about Powerpoint Presentations. *Journal of Technical Writing and Communication*, 38(2), pp. 149-165. <https://doi.org/10.2190/TW.38.2.d>
- Savoy, A., Proctor, R. W., Salvendy, G. (2009). Information retention from PowerPoint™ and traditional lectures. *Computers & Education*, 52(4), pp. 858-867. <https://doi.org/10.1016/j.compedu.2008.12.005>
- Szabo, A., & Hastings, N. (2000). Using IT in the undergraduate classroom: should we replace the blackboard with PowerPoint?. *Computers & education*, 35(3), pp. 175-187. [https://doi.org/10.1016/S0360-1315\(00\)00030-0](https://doi.org/10.1016/S0360-1315(00)00030-0)
- Tangen J. M., Constable M. D., Durrant E., Teeter C., Beston B. R., Kim J. A. (2011). The role of interest and images in slideware presentations. *Computers & Education*, 56, pp. 865–872. <https://doi.org/10.1016/j.compedu.2010.10.028>
- Wolfe, J., Shanmugaraj, N., Reineke, J., Caton Peet, L., Moreau, C. P. (2024). Advancing the Knowledge Base on Effective Presentation Slide Design: Three Pilot Studies. *Journal of Technical Writing and Communication*, 54(3), pp. 235-264. <https://doi.org/10.1177/00472816231169433>
- Yilmazel-Sahin, Y. (2009). A comparison of graduate and undergraduate teacher education students' perceptions of their instructors' use of Microsoft PowerPoint. *Technology, Pedagogy and Education*, 18(3), pp. 361-380. <http://dx.doi.org/10.1080/14759390903335866>

Authors' bios

Viviana Mangraviti, University of Padua (Italy)

Dr. Viviana Mangraviti is a Civil Engineer and Researcher in Geotechnics at the University of Padova, Italy. She earned her PhD cum laude in "Structural, Seismic and Geotechnical Engineering" from Politecnico di Milano in 2021, specializing in Geosynthetic-Reinforced and Pile-Supported embankments. Her postdoctoral work at Chalmers University of Technology, Sweden, focused on developing fully-coupled numerical analyses for slope stability under extreme climate events. Dr. Mangraviti's current research explores methodologies to evaluate levee system stability during floods, reflecting her expertise in geotechnical engineering and natural hazard mitigation. She currently serves as the chair of the International Geosynthetics Society (IGS) Young Members Committee, contributing to create connections among next-generation geotechnical engineers worldwide.

Lorenzo Brezzi, University of Padua (Italy)

Dr. Lorenzo Brezzi is Assistant Professor in Geotechnical Engineering at the University of Padova (Italy), where he teaches courses on foundations, environmental geotechnics, and geotechnical monitoring. His research focuses on landslide risk assessment, the interaction between geohazards and infrastructure, and innovative monitoring techniques such as fiber optic sensing and drone-based photogrammetry. He has contributed to the numerical modelling of both slow and rapid landslides, and to the development of risk assessment methodologies for bridges and viaducts within the FABRE framework. Dr. Brezzi is a member of the National Group for Geotechnical Engineering (GNIG), where he serves as the representative of Italian early-career researchers. He actively participates in public outreach activities, such as Science4All. Internationally, he serves as lecturer in the Erasmus Mundus Master "NoRISK" and in the national Master on the safety assessment of existing infrastructures (FABRE Master), and he is involved in academic cooperation with ENSTP in Cameroon. In 2024, he was invited as a guest lecturer at the China University of Geosciences (Wuhan), presenting his research on landslide–infrastructure interaction.

Giorgia Dalla Santa, University of Padua (Italy)

Giorgia Dalla Santa is a Researcher (RtdB) at the University of Padua (Italy). Her research focuses on soil characterization as well as levee monitoring and stability assessment. Additionally, she specializes in energy geostructures and shallow geothermal systems for building conditioning. Regarding teaching, she is responsible for the courses "Geotechnics" and "Safety in Excavations" in the master's programs at the Department of Geosciences, and the course entitled "Geothermal Systems for a Sustainable

Environment" in the Environmental Engineering master's program. She has also been involved in the international teaching program Engineering for Africa, a collaboration between the University of Padua (Italy) and the École Nationale des Travaux Publics (Cameroon).

Fabio Gabrieli, University of Padua (Italy)

Fabio Gabrieli is an Associate Professor of Geotechnical Engineering at the University of Padua. He graduated in Environmental and Land Engineering in 2005 and obtained his Ph.D. in Civil and Environmental Engineering in 2009 with a dissertation on the application of particle-based numerical methods for modeling landslide initiation in granular soils. His research focuses on granular soil mechanics, soil–structure interaction, numerical modeling with discrete element methods (DEM), and advanced geotechnical monitoring techniques, with particular attention to landslides, river embankments, and protective earth structures. He has participated in national and international research projects, contributing to the development of innovative methods for slope stability assessment and geotechnical risk mitigation. In teaching, Prof. Gabrieli lectures in “Geotechnics,” “Geotechnical Design in Land Protection,” “Ground Improvement,” within the degree programs in Civil Engineering and Environmental Engineering. He is a member of the Ph.D. board in Civil, Environmental, and Architectural Engineering, where he also teaches “Advanced Soil Mechanics” to doctoral students. He has supervised more than 100 master's and doctoral theses. He is the author of numerous scientific publications in international journals and has actively participated in conferences and workshops in the field of geotechnical engineering and land protection.

Francesca Ceccato, University of Padua (Italy)

Francesca Ceccato is associate professor at the University of Padua (Italy), where she currently teaches “Geological and Geotechnical Engineering” and “Numerical Modelling in Geomechanics” in the master programs of Water and Geological Risk Engineering and Civil Engineering. She has also been involved in the international teaching program Engineering for Africa within the cooperation between the University of Padua (Italy) and the Ecole Nationale des Travaux Publics (Cameroon). She is the secretary of TC103-Numerical methods of ISSMGE, and member of TC-306-Geoengineering education. Her main research topics include numerical modelling in geomechanics, with particular interest in the Material Point Method (MPM). She is member of the core developer team of the open-source code Anura3D, based on MPM, and participate intensively in the activities of the Anura3D MPM research community including the organisation of training courses.

***Priority Theme 1:
Teaching of Unsaturated Soils***

Integrating soil suction in geotechnical education: a case study on partially saturated slope stability analysis in Sweden

A. Abed & M. Karstunen

Chalmers University of Technology, Gothenburg, Sweden
ayman.abed@chalmers.se, minna.karstunen@chalmers.se

ABSTRACT: This paper explores the teaching of shear strength in partially saturated soils, emphasizing the role of suction in slope stability—a key concept in geotechnical engineering in the face of growing climate-related challenges. Through a problem-based coursework, students analyse a silty slope in Sweden under two scenarios: one following the traditional approach of neglecting suction and another incorporating it using established theoretical models. Students are provided with comprehensive in-situ data, including slope geometry, CPT data, water content, bulk density, grain size distribution, Soil Water Characteristic Curves (SWCC), and precipitation data, to simulate real-world conditions. Missing parameters are estimated using empirical correlations. Through GeoStudio software (Slope/W and Seep/W), students evaluate slope stability under hydrostatic and varying infiltration conditions. Findings highlight the importance of soil suction in slope stability, particularly in regions like Sweden, where increased rainfall and wetting/drying cycles have made this a critical issue. The coursework has been well received, providing students with practical skills to address soil stability in changing environmental conditions while also highlighting the importance of integrating soil suction into geotechnical education.

Keywords: Teaching, Slope stability, Unsaturated soil mechanics, Suction

1 Introduction

With climate change causing rising temperatures and more extreme weather events—such as heavy rainfall and prolonged dry periods—significant shifts in Sweden's climate are expected over the next 25 years (SOU, 2007). This will create a significantly partially saturated zone at the ground surface, which is a key concern in practical civil engineering applications. To address this, future engineers cannot rely solely on classical soil mechanics; they must also develop at least a basic understanding of unsaturated soil mechanics (Fredlund et al., 2012).

In Sweden, shear strength has traditionally been taught under the assumption that the soil is fully saturated or fully dry. The primary focus has been on Terzaghi's effective stress as the key parameter for analysing soil behaviour in terms of deformation and stability. One of the most challenging aspects of this field is the stability of natural slopes. In particular, the stability of natural silty slopes has been a longstanding concern in Sweden, with an increasing number of documented slope failures in this type of soil (BIG A2022-01, 2024).

At Chalmers University of Technology, third-year students are introduced to fundamental concepts of soil mechanics (Knappett and Craig, 2019). They develop a strong understanding of undrained shear strength for short-term analysis and effective shear strength parameters for long-term drained conditions, always assuming that the soil consists of only two components: solid and water. Students are briefly introduced to capillary rise above the groundwater table and its effect on generating negative (tensile) pore water pressure. While the term "suction" is mentioned in this context, its implications for soil strength and stiffness are not explored in depth. As a result, students receive little formal education on unsaturated soil mechanics and the role of suction in the mechanical behaviour of soil.

This was one of the key motivations behind developing a relatively new course for fifth-year master's students in Civil Engineering at Chalmers: Contemporary Topics in Geomechanics (ACE230). This course is designed to provide students with advanced knowledge in geomechanics, equipping them to tackle contemporary challenges related to climate change and sustainability. The curriculum covers essential topics such as effective stress principles for partially saturated soils, variations in soil shear strength and stiffness due to saturation changes, and slope stability assessment under different conditions. Students also explore tunnelling methods in both soils and rocks, gaining an understanding of their environmental impacts. Sustainable ground improvement techniques—such as vertical drains, stone columns, deep mixing, and grouting—are examined as alternatives to traditional piling methods. Additionally, the course introduces soil dynamics, addressing key considerations for high-speed rail foundations and renewable energy projects. The course is delivered through a combination of lectures, tutorials (including computer-based exercises), and consultation sessions for design projects. Coursework is completed in groups (max four students), with individual assessments incorporated. The course is designed so that the students will have the expertise to analyse and apply geotechnical solutions that contribute to climate resilience and sustainable infrastructure development. However, only the part related to the unsaturated soil mechanics of the course will be discussed here.

This paper presents a case study of a student coursework project designed to teach the principles of soil suction and its impact on slope stability. It offers several key contributions by presenting a real-world case study of a silty slope in Sweden, demonstrating how suction influences slope stability analysis, providing an example of an effective educational approach to teaching this complex topic, and outlining the positive student response to the course.

2 Background

The coursework is designed to align with key concepts from the lectures, ensuring a constructive alignment between the intended learning outcomes and learning activities (Biggs, 2014). The lectures cover the following topics:

- Unsaturated soil characterization
- Stress measures in unsaturated soil
- Soil suction and the soil-water characteristic curve
- Groundwater flow in unsaturated soil
- Unsaturated slope stability
- A brief introduction to expansive soils

A key focus of the course is for students to understand the concept of suction, its components, and its relationship to stiffness and strength. The students are introduced to Bishop's effective stress and net stress, emphasizing the two main approaches to describing the mechanical behaviour of partially saturated soil:

1. The single stress measure method (Bishop's effective stress)
2. The two independent stress measures method (net stress and suction)

The advantages and drawbacks of each approach are discussed in detail (Gens et al., 2006). Ultimately, the course adopts the two independent stress measures as the preferred method for application in the coursework.

After establishing a solid understanding of suction and stress measures, the course introduces another important concept: the soil-water characteristic curve (SWCC). This includes an explanation of its physical meaning, experimental methods for measuring it, and the most common mathematical models used to fit experimental data, such as the van Genuchten (Van Genuchten, 1980), Fredlund-Xing (Fredlund and Xing, 1994), and Brooks-Corey (Brooks and Corey, 1966) functions. Additionally, the possibility of estimating the SWCC in the absence of experimental data—using basic soil properties like grain size distribution and Atterberg limits—is explored (Aubertin et al., 2003).

The effect of suction on soil hydraulic conductivity is also examined, introducing the hydraulic conductivity function and discussing how it can be derived based on the SWCC (Fredlund et al., 2012). Furthermore, the influence of suction on both water content and hydraulic conductivity is clarified through an analysis of the hydraulic behaviour of unsaturated soil, including an explanation of the water mass balance equation under transient conditions.

Two lectures are dedicated to discussing the shear strength of unsaturated soils and how it compares to the shear strength of fully saturated soils. A key focus is on the contribution of suction to increasing the shear strength of partially saturated soil by introducing an additional cohesion component, commonly referred to as capillary cohesion or apparent cohesion. The lectures also cover common methods for evaluating apparent cohesion, including its linear relationship with matric suction and its nonlinear increase as expressed in terms of the SWCC (Vanapalli et al., 1996).

To analyse the impact of suction on slope stability, the classical limit equilibrium method is first reviewed. Then, a modified approach that incorporates the effect of suction is introduced using the extended Mohr-Coulomb failure criterion for partially saturated soils (Fredlund et al., 2012).

Most importantly, the significance of considering suction variations in calculations is emphasized. The course also highlights the need to solve the unsaturated groundwater flow equation for accurate slope stability analysis. This is illustrated through examples that assess the evolution of safety factor under various hydraulic boundary conditions, such as infiltration and evaporation.

The hydraulic boundary conditions, influenced by extreme rainfall events and prolonged dry seasons, are particularly relevant, as observed in Sweden in the context of climate change. By reducing shear strength through a decrease in suction, they are strongly suspected to be a key triggering factor in the rising number of recorded failures in natural silty slopes. Stemming from these suction-related issues, a problem-based coursework was designed as problem-based learning is expected to improve knowledge retention (Beers and Bowden, 2005). Students were tasked with applying the knowledge gained in the course to analyse the stability of an actual natural slope, including the effect of suction under the effect of recorded precipitation data.

3 Case study: Silty slope in Sweden

The case study focuses on a silty slope located at the Skedomsvärdet test site in Sollefteå, Sweden, situated on a bank by the river Ångermanälven (Öberg, 1997). The site features a ravine, about 50 meters deep, at its northern boundary, with a steep, vegetated slope to the south. The surrounding area is developed with houses on the crests on both sides. A sliding event occurred near the houses in the early 1980s, prompting the installation of a gravel protection layer in the river at the bottom of the ravine to prevent further sliding. The soil at Skedomsvärdet consists mainly of non-cohesive materials, including medium and fine sand in the uppermost 5 meters, followed by silty sand down to about 10 meters, and silty soil at greater depths. The bedrock is located at the bottom of the river in the ravine.

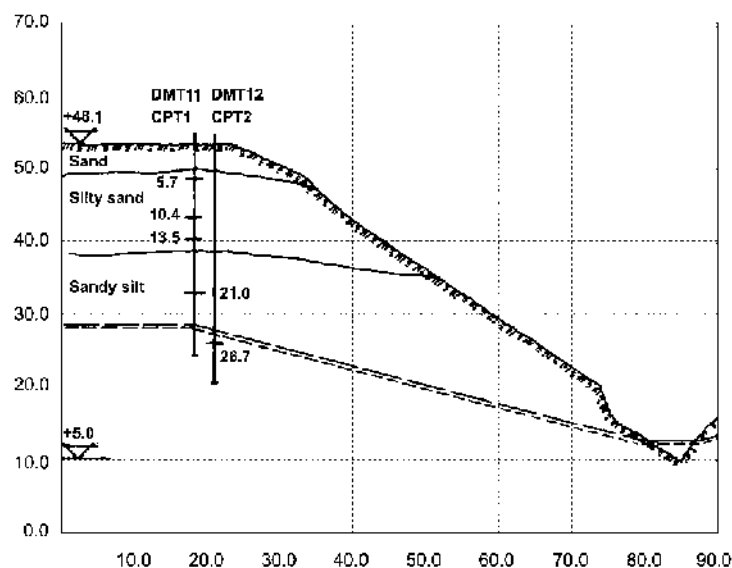


Figure 1. Slope geometry modified after Öberg (1997). Levels +5.0 and +48.1 are relative to sea level; soil sample depths (5.7, 10.4, 13.5, 21.0 and 26.7 m) are measured from ground level

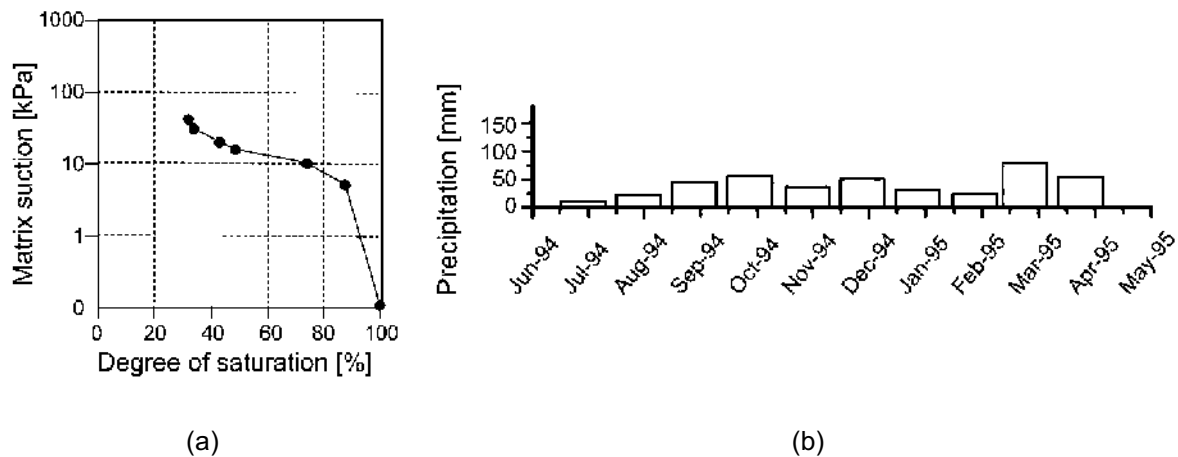


Figure 2. Example of the provided data to students: a) measured SWCC at a depth of 5.7 m; b) measured precipitation at the location of the slope modified after Öberg (1997)

For the analysis of stability of the slope, the students were provided with a range of in-situ data. This includes detailed slope geometry, which is outlined in documents showing sections and views of the test site, along with locations of boreholes and piezometers, see Figure .

The Cone Penetration Test (CPT) data reveals that the friction angle is approximately 32° in the upper 18 meters, decreasing to around 30° at greater depths. The natural water content of the soil varies between 5-15%, with the bulk density of saturated soil estimated to be around $1.8\text{--}1.9 \text{ t/m}^3$ ($18\text{--}19 \text{ kN/m}^3$). Grain size distribution curves show that the soils range from coarse silt to fine sand, with a clay content of about 2-3%. Soil Water Characteristic Curves (SWCCs), determined in the laboratory for samples from various depths, see Figure 2(a) as an example, illustrate the relationship between degree of saturation and matric suction. Real precipitation data for one full year is also provided, as it clear in Figure 2(b), to assess the impact of infiltration on the stability of the slope.

In addition to this data, the students were tasked with estimating some missing properties such as the saturated hydraulic conductivity using empirical correlations derived from the grain size distribution curves and basic geotechnical properties.

4 Methodology

4.1 Software used

For the slope stability analyses, students utilized GeoStudio software, specifically the Slope/W and Seep/W modules. GeoStudio is a well-known comprehensive suite of geotechnical software used for analysing slope stability, seepage, and other geotechnical problems. Slope/W is designed for slope stability analysis, allowing the inclusion of partial saturation and suction effects, while Seep/W is used to analyse groundwater seepage.

4.2 Analysis scenarios

4.2.1 Scenario 1: Neglecting the effects of suction (classical approach)

In the first scenario, students analysed the slope stability without considering the effects of suction. This classical approach neglects the effect of suction in the partially saturated zone by setting its value to zero. The input parameters and assumptions used in this scenario include:

- Slope geometry: The geometry of the slope, including the height, angle, and stratigraphy, was defined based on the provided site data.
- Soil properties: The soil properties, such as cohesion, friction angle, and unit weight, were obtained from the provided CPT data and laboratory tests.

- Pore-water pressure: The pore-water pressure and phreatic level were calibrated by running a steady-state water flow analysis based on the provided hydraulic boundary conditions, including the water level in the river and measured piezometric levels in different locations on the slope.

4.2.2 Scenario 2: Considering the effects of suction

In the second scenario, students analysed the slope stability by considering the effects of suction using different theoretical models for shear strength and for the SWCC. The explored models for SWCC include the van Genuchten (VG) model and the Fredlund-Xing (FX) model as well as deriving the SWCC based on basic soil properties (Aubertin et al., 2003). The later analysis was carried out to mimic the situation in the absence of measured SWCC data and to check the accuracy of such an approximation. The input parameters and assumptions used in this scenario include:

- Slope geometry: The same slope geometry as in Scenario 1 was used.
- Soil properties: The soil properties were the same as in Scenario 1, with additional parameters for the SWCC.
- SWCCs: The Soil Water Characteristic Curves (SWCCs) were determined from laboratory tests and used to define the relationship between soil suction and water content. The VG and FX models were used to fit the SWCC data using an in-house Python script, which was run using Jupyter Notebook.
- Pore-water pressure: The pore-water pressure distribution was calculated using Seep/W, considering both saturated and unsaturated flow conditions.
- Precipitation data: Real precipitation data, Figure 2(b), was used to simulate infiltration events and their impact on pore-water pressure and slope stability. The effects of suction variation were incorporated into the stability analysis once, assuming a linear relationship between apparent cohesion and suction, and another time assuming a nonlinear relationship (Vanapalli et al., 1996).

4.3 Student workflow

The group work process was designed to guide students through the analysis in a structured manner. The workflow included the following steps:

- Data collection: Students collected and reviewed the provided site data, including slope geometry, CPT data, soil properties, SWCCs, and precipitation data.
- Software familiarization: Students were introduced to GeoStudio software and its modules, Slope/W and Seep/W. They learned how to input data, define analysis parameters, assign different types of hydraulic boundary conditions and interpret results.
- Parameter estimation: Students estimated any missing parameters, such the saturated hydraulic conductivity, using empirical correlations and engineering judgment.
- Scenario analysis: Students performed the slope stability analysis for both scenarios. They first analysed the slope using the classical approach (Scenario 1) and then considered the effects of suction (Scenario 2) using the VG, FX and estimated SWCC models.
- Results interpretation: Students compared the results of both scenarios, discussing the impact of suction and SWCC on slope stability. They evaluated the differences in factor of safety and identified potential failure mechanisms.
- Reporting: Students documented their analysis, results, and conclusions in a comprehensive report. They included detailed descriptions of the input data, analysis methods, and findings.

Throughout the process, students were guided by the instructor who provided feedback and support. The structured workflow ensured that students gained hands-on experience with GeoStudio software and developed a thorough understanding of groundwater flow and slope stability analyses considering partial saturation and suction effects.

5 Students' results

5.1 Scenario 1: Neglecting the effects of suction (classical approach)

In the classical approach, the slope stability analysis was performed without considering the effects of suction. The factor of safety (FoS) was calculated by most of the students' groups to be just below 1.0, indicating that the slope should have failed. However, in reality, it remains stable. This already satisfies one of the pedagogical learning outcomes by helping students understand the contribution of suction in maintaining slope stability. It also highlights that the slope is marginally stable. The critical slip surface was identified as shallow, indicating potential instability near the surface. It was observed, however, that even in this relatively simple task, the reported FoS varied among the groups. This variation may be attributed to slight differences in the adopted geometry, decisions regarding soil layering, and assumptions made about missing data.

5.2 Scenario 2: Considering the effects of suction

In this scenario, slope stability analysis was conducted by incorporating the effects of suction using the VG and FX models, along with estimated SWCCs based on basic geotechnical data. The slope was subjected to recorded precipitation data for one full year as an infiltration boundary condition.

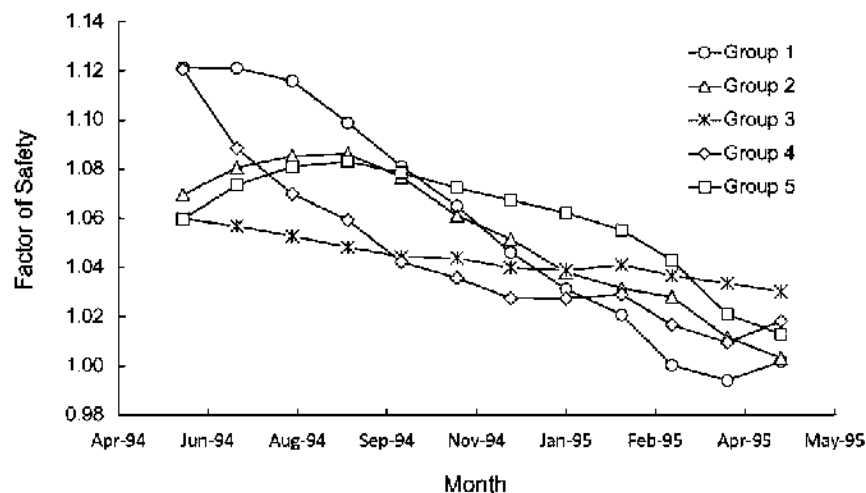


Figure 3. Students' predictions for the variation of FoS assuming FX model for SWCC and a linear relationship between suction and apparent cohesion

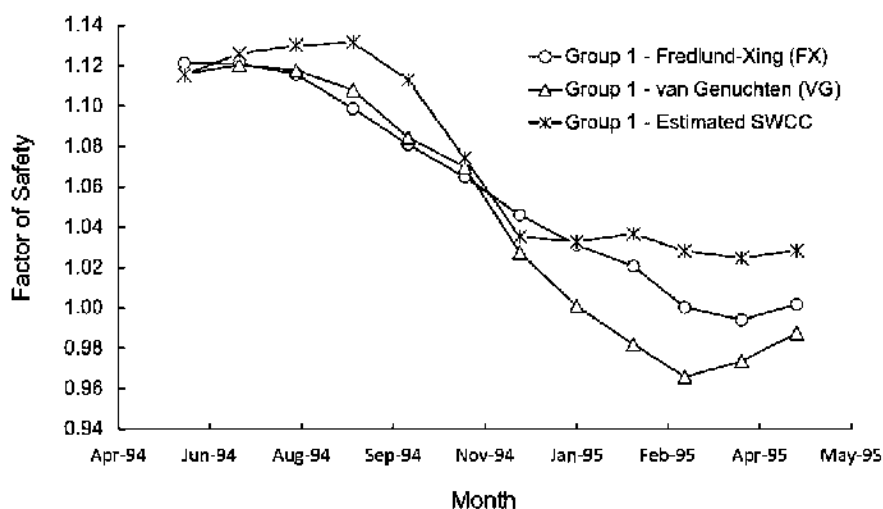


Figure 4. Group 1 predictions for the variation of FoS assuming different models for SWCC and a linear relationship between suction and apparent cohesion

On the one hand, Figure presents an example of the predictions made by different student groups using the FX model for SWCC. The results in this figure correspond to the case where apparent cohesion was assumed to have a linear relationship with matric suction. On the other hand, Figure shows the results of Group 1 when assuming different models for the SWCC (i.e., VG, FX, and those estimated based on basic geotechnical properties).

6 Educational impact and student feedback

6.1 Effect of suction variation on slope stability

This coursework provided students with a deeper understanding of how variations in suction influence the stability of partially saturated natural slopes. They observed that rainfall events significantly alter suction levels, leading to fluctuations in the factor of safety (FoS). Unlike in conventional saturated soil analyses, where FoS is typically a fixed value, students recognized that in unsaturated conditions, it is highly dynamic. The safety factor is not a single, constant number but varies as a function of suction and applied environmental loads, such as infiltration from rainfall.

6.2 The role of SWCC in unsaturated soil analysis

The Soil Water Characteristic Curve (SWCC) played a crucial role in this study, providing the necessary relationship between soil suction and water content. Students learned that the accuracy of slope stability predictions in unsaturated conditions is highly sensitive to how the SWCC is estimated. The van Genuchten (VG) and Fredlund-Xing (FX) models both provided reliable results, as they both rely on fitting measured data, demonstrating their effectiveness in capturing unsaturated soil behaviour. However, the students also recognized the potential risks of applying these models in the absence of sufficient experimental data. When data is limited, careful estimation of SWCC parameters is critical to avoid misrepresenting the slope's response to environmental changes.

6.3 Student insights and key takeaways

Through their analyses, students concluded that incorporating matric suction into slope stability assessments provides a more realistic representation of slope behaviour. They observed that the FoS increased remarkably when suction was considered, highlighting the stabilizing effect of reduced pore water pressure. However, they also noted that during intense rainfall, suction decreases, leading to a reduction in the FoS, reinforcing the need for mitigation measures in marginally stable slopes.

The variability in FoS across different student groups further emphasized how different assumptions about soil layering, SWCC estimation, and missing data impact the final stability predictions. This variability underscored the importance of using well-calibrated SWCC models and ensuring that input data accurately represent site-specific conditions.

As a complementary part of the coursework to mitigate rainfall-induced shearing failure, students explored stabilization strategies such as horizontal drains and nature-based solutions (NBS), including live crib walls. These measures were recommended to enhance slope stability by controlling infiltration and maintaining sufficient suction levels in the soil.

7 Conclusions

Integrating suction effects into slope stability assessments helped students understand the transient nature of the factor of safety (FoS) in unsaturated conditions. They recognized the need for advanced methods beyond traditional saturated soil mechanics, particularly for rainfall-induced instability. The coursework output emphasized the careful selection of SWCC models, which become particularly challenging when data is limited.

While the project looked at how different ways of representing the SWCC affect the factor of safety, there are other important sources of uncertainty—like how we estimate soil strength from CPT tests, which is still a difficult and developing area in unsaturated conditions. Also, the role of the hydraulic conductivity function was not fully discussed, even though it strongly affects how water moves through

the soil and influences suction during infiltration events. In future, more attention will be given to this function, so students understand its importance, rather than seeing it as something secondary. It would also be beneficial to emphasize the idea that soils behave differently when wetting and drying, and that using different curves for each case makes the analysis more realistic, especially when dealing with long periods of rainfall and evaporation.

Introduced three years ago, the ACE230 course has received consistently excellent feedback from students for its structured coursework, clear learning outcomes, and the constructive alignment between learning outcomes, learning activities and examining parts. Its success underscores the value of teaching unsaturated soil mechanics, equipping future engineers with essential skills to address evolving geotechnical challenges.

Acknowledgements

The authors would like to thank the Chalmers MSc students for providing the data used in this paper. We are also grateful to the two anonymous reviewers for their insightful comments and suggestions.

References

- Aubertin, M., Mbonimpa, M., Bussière, B., Chapuis, R.P., 2003. A model to predict the water retention curve from basic geotechnical properties. *Can. Geotech. J.* 40, 1104–1122.
- Beers, G.W., Bowden, S., 2005. The effect of teaching method on long-term knowledge retention. *J. Nurs. Educ.* 44, 511–514.
- BIG A2022-01, 2024. Långsamma skred i skitad siltig jord.
- Biggs, J., 2014. Constructive alignment in university teaching. *HERDSA Rev. High. Educ.* 1, 5–22.
- Brooks, R.H., Corey, A.T., 1966. Properties of porous media affecting fluid flow. *J. Irrig. Drain. Div.* 92, 61–90.
- Fredlund, D.G., Rahardjo, H., Fredlund, M.D., 2012. *Unsaturated Soil Mechanics in Engineering Practice*. John Wiley & Sons.
- Fredlund, D.G., Xing, A., 1994. Equations for the soil-water characteristic curve. *Can. Geotech. J.* 31, 521–532.
- Gens, A., Sánchez, M., Sheng, D., 2006. On constitutive modelling of unsaturated soils. *Acta Geotech.* 1, 137–137.
- Knappett, J., Craig, R.F., 2019. *Craig's soil mechanics*. CRC press.
- Öberg, A.-L., 1997. Matrix suction in silt and sand slopes. Significance and practical use in stability analysis. Chalmers University of Technology.
- SOU, S., 2007. Sweden facing climate change—threats and opportunities. Stockh. Swed. Comm. Clim. Vulnerability SCCV.
- Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils 1. *Soil Sci. Soc. Am. J.* 44, 892–898.
- Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E., Clifton, A.W., 1996. Model for the prediction of shear strength with respect to soil suction. *Can. Geotech. J.* 33, 379–392.

Authors' bios

Ayman A. Abed, Chalmers University of Technology (Sweden)

Dr. Ayman abed is a Senior Lecturer in the Division of Geology and Geotechnics, research area Geotechnics. He is interested in studying the coupled thermo-hydro-mechanical-chemical (THMC) behaviour of unsaturated soil. One of the main purposes of his research is to provide practical engineering solutions to confront the challenges associated with global climate change. Ayman is an expert in unsaturated soil mechanics, constitutive modelling, and numerical analyses. His dedication to education was recognized when he was awarded the Student's Pedagogical Prize 'Teacher of the Year 23/24' at Civil and Environmental Engineering, Chalmers University of Technology.

Minna Karstunen, Chalmers University of Technology (Sweden)

Minna Karstunen is Professor in Geotechnical Engineering at Chalmers University of Technology, and a Fellow of the Institution of Civil Engineers, UK. Minna got her PhD at the University of Wales Swansea in 1998 followed by a successful academic career in the UK, at the Universities of Glasgow (1996-2005) and Strathclyde (2005-2013). Minna joined Chalmers in 2012, where she is leading a dynamic research group working on modelling and characterisation of complex natural and engineered geomaterials, aiming to bridge fundamental understanding with applications in engineering practice. Even though Minna is internationally known for her research on constitutive model development, in parallel, she has been working on other topics, including novel numerical techniques for representing periodic ground improvement on soft soils.

Why unsaturated soil mechanics is relevant to civil engineers

K.V. Bicalho

Federal University of Espirito Santo, Vitoria, ES, Brazil

katia.bicalho@ufes.br

ABSTRACT: This paper emphasises the benefits of introducing fundamental principles of unsaturated soil mechanics (UNSAT SM) to undergraduate courses in civil (and environmental) engineering. It highlights the usefulness of understanding or knowing the behaviour of partially saturated soil systems in geotechnical engineering practice. The paper discusses the relevance of ground moisture conditions (and corresponding pore water pressures) to geotechnical site investigation and soil tests interpretation due to ground water level changes that could be used for demonstrating to students unsaturated stress analysis applied for geo-works stability investigation. The paper lists some reference sources emphasizing the principles of unsaturated soils. Some examples related to UNSAT SM of what can be taught in soils mechanics classes without changing the workload in undergraduate civil engineering curriculum are also presented. Finally, suggestions for expanding beneficial collaboration strategies between technical Committees of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) are discussed.

Keywords: Unsaturated soil mechanics, Learning and teaching, Geotechnical engineering education

1 Introduction

Unsaturated soil conditions are common encountered in both natural geological formations and man-made earth constructions. Unsaturated soil mechanics (UNSAT SM) is relevant to civil engineers because infrastructures are commonly constructed above the groundwater table (WT) and compacted unsaturated soils are widely used in earth structures. Thus, geotechnical civil engineers routinely deal with unsaturated soils (Houston, 2024).

Despite the impressive research developments in UNSAT SM in recent decades, undergraduate geo-engineering students are generally taught only the two limiting conditions: completely dry (no water) or completely water-saturated soils (no air). The used term "unsaturated" means "partially saturated" and indicates S (water degree of saturation) < 1 and a third phase is introduced into the two-phase water saturated soil. Soil water saturation (and corresponding pore water pressures) may vary within a wide range in soil foundation above the WT and earthwork exposed to environmental changes. The variations in geotechnical properties due to climatic change impacts may be significant.

Water plays an active role in geotechnical engineering. Discussions related to the dependence of saturation on negative pore water pressure (often named soil suction) and the role of soil saturation variation in changing soil properties should be presented in introductory courses in soil mechanics. This is not an easy task, even the definition of UNSAT SM is an academic challenge itself (Lu & Likos, 2004). But it is relevant for geo-engineering instructors and students to see how important it is for them to explore and apply UNSAT SM in geo-engineering problems or challenges (such as soil profiles investigation, and stability of foundation systems and geotechnical structures).

An unsaturated soil is just a state of the soil, not a special type of soil (Gens et al., 2006). Several conferences organized under the auspices of the ISSMGE have been held to disseminate knowledge and reliable practice in the field of UNSAT SM since the first international conference on unsaturated soils in 1995. These conferences have showcased remarkable advances in fundamental knowledge, testing methods, prediction models and geotechnical practice. This paper lists sources of relevant

research comprising special lectures, state-of-the-art and state-of-the-practice on dealing with unsaturated soils and emphasizing the principles of unsaturated soils.

Houston (2024) presents and discusses some key topics for introducing unsaturated soils, such as: UNSAT stress state should be evaluate with consideration of total stress (net stress) and negative pore water pressure (suction); soil suctions should not be “conservatively” assumed zero; shear strength and volume change of UNSAT soils are dependent on soil suction, as well as confining stress, and site investigations and testing must account for both stress variables; water follows Darcy’s law, but hydraulic conductivity is a non-linear function of water content; UNSAT response requires testing and simulation data, and their interpretation. Some examples related to UNSAT SM (i.e., soil profiles, state variables & shear strength, compacted soils, stability analysis of UNSAT slopes) of what can be explored in soils mechanics undergraduate classes without changing the workload in undergraduate civil engineering curriculum are presented herein.

The main goals of the article are: (1) to emphasize the benefits of introducing fundamental principles of UNSAT SM to undergraduate courses in geo-engineering, (2) to explore possible applications of UNSAT SM in some geotechnical problems and (3) to motivate geo-engineering instructors and students to read literature dealing with UNSAT SM.

2 Unsaturated soil mechanics (UNSAT SM) resources

For learning and teaching, it is helpful to recognize the diverse ways in which geo-structures subjected to environmental changes can fail. It is important for educators to motivate students to study UNSAT SM, and this will not be possible if the geo-engineering teachers do not recognize the importance of identifying and understanding relevant main topics for introducing UNSAT SM.

Material presented in the UNSAT SM textbooks (i.e., Fredlund & Rahardjo, 1993; Lu & Likos, 2004) provides necessary background including fundamental principles and concepts for teachers and students interested in the subject. It is important to mention that in UNSAT SM books emphasis is also placed on the transition from unsaturated to saturated soil conditions or vice versa (Blight, 2017; Briaud, 2013). Although the main reference sources for UNSAT SM are publications of the geotechnical engineering, contributions have also come from hydrology, soil science petroleum, and reservoir engineering (Corey, 1994).

2.1 Some ISSMGE (TC106) initiatives

An open access education platform from ISSMGE is dedicated to recorded webinars, which cover unsaturated soils basic concepts and applications, see webinars by Alonso (2012) and Fredlund (2019). Moreover, the website “Introducing Unsaturated Soil Mechanics in the Undergraduate Curriculum”, funded by the National Science Foundation (NSF) and developed by Houston et al. (2014), includes educational material for professors planning to include unsaturated soil mechanics into current undergraduate curricula.

Over the last decades, the domain of UNSAT SM has begun to receive increasing attention worldwide, and several international and regional (European, Asia-Pacific, American) conferences under the general heading of Unsaturated Soils (UNSAT) have been held to disseminate knowledge and reliable practice in the field of UNSAT SM including as examples, expansive, collapsible, residual, and compacted soils. The International Conference on UNSAT series began in Paris in 1995 (UNSAT 1995). The Asia UNSAT series began in Singapore in 2000, and it has been extended to the Asia-Pacific region to reflect the geographic position of Australia (Asia-Pacific UNSAT series). The first European UNSAT series (E-UNSAT) was held in Durham in 2008. The first Pan-American UNSAT conferences series began in Cartagena de Indias, Colombia, in 2013 (i.e., Pan-American UNSAT 2013).

The Technical Committee Unsaturated Soils (TC106) of the ISSMGE plays a leading role in the promotion of the UNSAT conferences. The UNSAT proceedings include a collection of selected and invited papers comprising special lectures, state-of-the-art and state-of-the-practice on dealing with UNSAT. Even though different topics are emphasised in the international and regional UNSAT conferences, the UNSAT publications constitute essential references for academic, researchers and practitioners. Tables 1 and 2 present a summary (i.e., year and location) of the past international (UNSAT) and regional conferences series, respectively, held at approximately regular intervals in different countries and regions. It is also important to mention the contributions of a successful series of

conferences in USA, namely the ASCE Unsaturated Soils sessions in Dallas in 1993, in Logan (Geo-Logan) in 1997, and in Denver (Geo-Denver) in 2000. Expansive soils problems, which are often considered a theme of UNSAT, represent a large problem in many countries. The seven International Conferences on Expansive Soils held from 1967 to 1992 discuss significant practical issues in geotechnical engineering.

The proper determination of the relationship between water content and corresponding pore-water pressure and the interpretation of soil moisture monitoring to engineering behaviour of geo-works is one of the major challenges in the experimental UNSAT SM. Well-designed laboratory and field techniques to determine soil properties including twelve reports by leading researchers from fourteen countries have been presented and discussed in the International Symposium on Advanced Experimental Unsaturated Soil Mechanics held in Trento, Italy (Tarantino et al. 2005).

Table 1. A summary of the past international UNSAT conferences series

UNSAT series (year)	Local
UNSAT'95	Paris, France
UNSAT'98	Beijing, China
UNSAT 2002	Recife, Pernambuco, Brazil
UNSAT 2006	Carefree, Arizona, USA
UNSAT 2010	Barcelona, Spain
UNSAT 2014	Sydney, Australia
UNSAT 2018	Hong Kong
UNSAT 2023	Milos, Greece

Table 2. A summary of the past regional (Asia-Pacific, E-UNSAT, Pan-American) UNSAT conferences

Regional UNSAT series (year)	Local
UNSAT- ASIA 2000	Singapore
UNSAT-ASIA 2007	Nanjing, China
E-UNSAT 2008	Durham, UK
Asia-Pacific UNSAT 2009	Newcastle, Australia
Asia-Pacific UNSAT 2011	Pattaya, Thailand
E-UNSAT 2012	Napoli, Italy
Pan-American UNSAT 2013	Cartagena de Indias, Colombia
Asia-Pacific UNSAT 2015	Guilin, China
E-UNSAT 2016	Paris, France
Pan-American UNSAT 2017	Dallas, United States
Asia-Pacific UNSAT 2019	Nagoya, Japan
E-UNSAT 2020	Lisbon, Portugal
Pan-American UNSAT 2021	Rio de Janeiro, Brazil (on-line)
Asia-Pacific UNSAT. 2024	Melbourne, Australia
E-UNSAT 2025	Lisbon, Portugal
Pan-American UNSAT 2025	Ottawa, Canada

3 Examples of what can be explored in UNSAT SM undergraduate classes

A few examples to introduction of UNSAT SM in soils mechanics undergraduate classes are also presented herein: soil profiles, state variables & shear strength, compacted soils, and stability analysis of UNSAT slopes.

Ground profile

Figure 1 (adapted by Bicalho, 2024) illustrates the importance of including meteorological information to site investigation by using in situ CPT data (Lehane et al., 2004) in sand above the WT. Suctions in sands and gravels above the WT are often assumed to be small with little impact on soil properties. Figure 1 shows a wide soil resistance penetration (CPT data qc) variation associated to saturation (water content) and soil suction variation during dry and wet seasons. The results indicate that periodical drying-wetting cycles can alter significantly soil seepage and stability analysis in earth works due to soil surface

atmosphere interaction. Soil surface suctions (and moistures) respond directly to wetting by infiltration of rainfall or drying because of evapotranspiration. The CPT q_c data over a long period is important to help quantify the influence of soil atmosphere fluxes in the soil work performance over time and evaluate soil behavior changes as function of both space and time in the soil profiles, and applied mechanics. The called unsteady “active” zone based on the in situ-controlled CPT data in a sandy soil above the WT for a specific site and time presents a relative deep depth (about 7m).

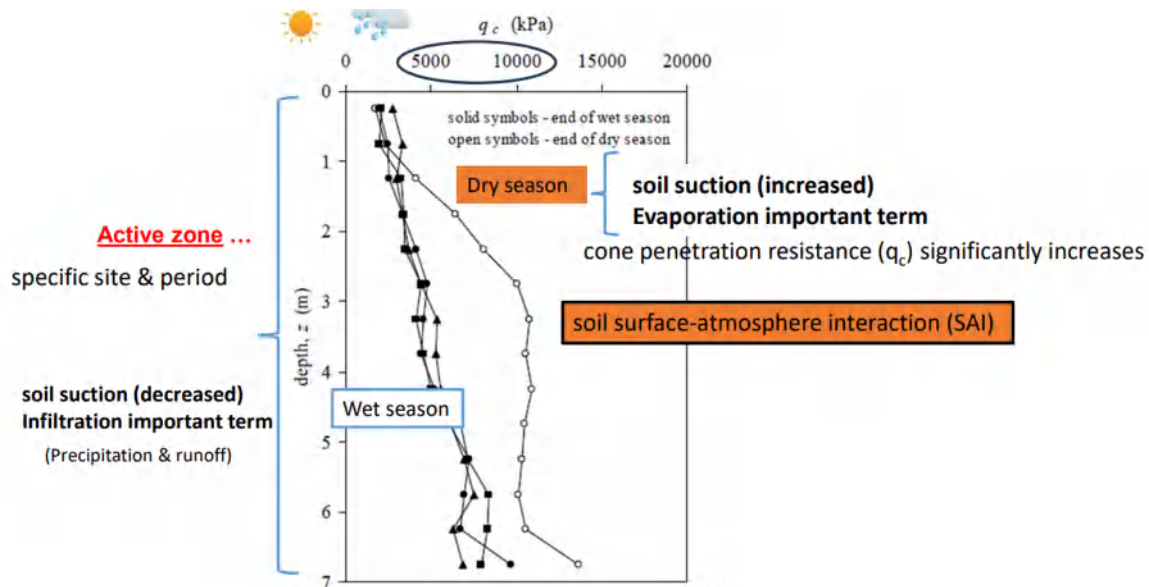


Figure 1. Effect of seasonal ground moisture conditions (and suctions) to site investigation by using in situ-controlled CPT data in sand above the ground water table (WT) (source data: Lehane et al., 2004)

The soil profile is influenced by many factors (i.e., the soil type, the thickness of the unsaturated zone and the fluid fluxes at the subsurface-atmosphere interface (Lu & Likos, 2004). Practical examples illustrating the influence of rainfall on slope stability and settlement of shallow foundations when the ground water level changes could be used for demonstrating to undergraduate civil engineering students unsaturated stress analysis applied for slope stability investigation.

State variables & shear strength

The use of UNSAT SM in practice requires that the traditional introductory geotechnical courses present information on unsaturated soil property functions [i.e., soil water retention SWR (or characteristic) and unsaturated hydraulic conductivity functions], including discussion on the importance of the two independent stress state variables for unsaturated soil conditions, i.e., the difference between the pore air pressure and the pore water pressure or matric suction ($u_a - u_w$) and net normal stress ($\sigma - u_a$). For example, the empirical Mohr-Coulomb shear strength criterion often used for saturated soils can be extended for unsaturated soils as follows (Fredlund et al., 1978; Leong et al., 2001):

$$\tau = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \quad (1)$$

where τ is shear strength, c' is effective cohesion, ϕ' is effective angle of friction and ϕ^b is the angle describing change in shear strength due to change in matric suction. As the soil becomes saturated, u_w approaches u_a , hence equation (1) reduces to the Mohr-Coulomb shear strength criterion for saturated soils (Leong et al., 2001). Moreover, many unsaturated mechanical and hydraulic soil properties can be obtained indirectly using the relationship between gravimetric or volumetric water content or degree of saturation and soil suction (i.e., SWR data).

The effects of negative pore-water pressure (i.e., soil suction) changes on soil properties can be significant. Leong et al. (2001) discuss the role of the SWR data in determining permeability and shear strength data in UNSAT. The experimental data obtained from Leong et al. (2001) for the increase of shear strength for two Singapore residual soils, Soil 1 and Soil 2, are reproduced in Tables 3 and 4 (the soils have different SWR data and initial void ratios). Their calculations for shear strengths (equation 1) for the two residual soils with $(\sigma - u_a) = 0$ are consistent with the experimental data. With the shear strength

parameters, they calculated normalized bearing capacity and factor safety, FS, for slope stability (Tables 3 and 4). Leong et al. (2001) show that the $FS < 1$ for Soil 2 at zero suction and becomes $FS > 1$ for 25 kPa suction value. The FS for Soil 1 does not show any further improvement for matric suctions > 100 kPa. Soil 1 does not exhibit any significant improvement in bearing capacity either beyond $u_a - u_w = 100$ kPa, since its shear strength reaches a plateau after a matric suction of 100 kPa.

Table 3. A summary of the effect of suction on normalized bearing capacity (i.e., N_{BC}) for two different residual soils (data from Leong et al., 2001)

Matric Suction ($u_a - u_w$) (kPa)	Shear Strength Soil 1, (τ) (kPa)	N_{BC} Soil 1	Shear Strength Soil 2, (τ) (kPa)	N_{BC} Soil 2
0	10	1.000	10	1.000
50	30	1.718	35	2.419
100	50	1.955	50	3.213
150	58	2.019	55	3.728
200	60	1.996	54	4.099
300	60	1.876	-	4.615

Table 4. A summary of the effect of suction on slope stability (i.e. Factor safety, FS) for two different residual soils (data from Leong et al., 2001)

Matric Suction ($u_a - u_w$) (kPa)	Shear Strength Soil 1, (τ) (kPa)	Factor safety, FS Soil 1	Shear Strength Soil 2, (τ) (kPa)	Factor safety, FS Soil 2
0	10	1.211	10	0.730
50	30	1.996	35	1.313
100	50	2.271	50	1.620
150	58	2.343	55	1.825
200	60	2.321	54	1.975
300	60	2.183	-	2.183

Tables 3 and 4 show that soil suctions should not be “conservatively” assumed zero in partially saturated soils: the increase in bearing capacity and slope stability due to the increase in matric suction that occur in the field under natural changing climate conditions depends on the material type, state variables, initial conditions and constitutive relationships (i.e., SWR data). Specification of the properly input data are required for appropriate modelling (i.e., prediction process for simplifying the actual problem).

Learning materials to a level that would be accessible by geotechnical engineering students with well-documented case histories particularly of geotechnical engineering could be presented and discussed in undergraduate (summarized examples) and graduate courses (several possibilities to interpret the resulting data) to illustrate the relevance of UNSAT SM in practice, the connection between theory and practice, the determination of the required soil parameters, and the capabilities of the models and computational tools in the characterization, prediction and interpretation of the experimental data. Students would be encouraged to identify actual case histories related to applications of unsaturated soil mechanics. Case histories from the perspective of unsaturated soil mechanics include sub-themes such as: embankments and earth dams, flow and infiltration, foundations, geo-environmental problems, isolation barriers, pavements, soil-atmosphere interaction, soil cover systems for waste containment, slope stability, thermal problems, engineering applications and field monitoring. Moreover, compacted soils are unsaturated soils widely used in civil engineering.

Compacted soils

Tatsuoka & Correia (2016) indicate the importance of controlling the degree of saturation (S) in specification and quality control of compacted fine-grained soils. Tatsuoka & Correia (2016) report that the called optimum degree of saturation, S_{OPT} (i.e., S of the maximum dry density obtained for a given compaction energy level (CEL) and a given soil type) can be used for controlling soil compaction. The value of S_{OPT} is insensitive to variations in CEL and soil type, which inevitably vary thus are usually unknown in the field. Therefore, it is proposed to examine whether S of compacted soil is close to S_{OPT} and dry density becomes large enough to ensure soil properties required in design. The results increase emphasis for the great interest of the SWR data in geotechnical engineering practice.

Stability analysis of UNSAT slopes

Ng & Leung (2011) present and discuss several geotechnical problems and case histories from the perspective of UNSAT SM, which could be used by educators in both undergraduate and graduate geotechnical courses. Soil saturation variation (i.e., WT, infiltration and evaporation) is a main contributor to the occurrence of slope failure. For example, rainfall infiltration can increase soil moistures, leading to the loss of soil suctions and decrease of soil shear strength. Batali & Andreea (2016) consider unsaturated soils above water table in the slope stability analysis for both cases of soil infiltration and drainage processes. It is considered different methods for estimating the shear strength variations depending on soil unsaturated conditions. Experimental data with site monitoring of suctions (drainage) and laboratory testing were used in the numerical slope stability analysis.

There are several commercially available finite-element-based softwares (e.g., Plaxis LE and GeoStudio) on seepage and stability analysis of partially saturated slopes subjected to rainfall infiltration available to consider different ways to model unsaturated seepage and shear strength of the soils that could be used by educators in both undergraduate and graduate geotechnical courses.

4 Building on existing collaborative approaches

Although the technical Committees of the ISSMGE have distinct main objectives it is important to expand technical Committees collaborations (i.e., Unsaturated Soils, TC106, and Geo-engineering Education, TC306) to develop both learning and teaching materials (i.e., spreadsheets, slide presentations, videos and software) in unsaturated soils for undergraduate geotechnical engineering courses. Positive and effective collaborations between TC103 and TC306 members to discuss specific issues related to UNSAT SM help to promote knowledge in UNSAT SM. Pantazidou et al. (2024) present a team project collaboration between TC103 and TC306 members on the specific issue of teaching UNSAT SM and the broader issue of some disagreement within the unsaturated soils community. Collaboration with regional technical committees in local and global contexts is also important, as well as establishing links between saturated and partially saturated soil mechanics concepts focusing on specific local soils, practices and technologies.

Software for numerical modelling of the behaviour of saturated and partially saturated soil systems is a required tool for analysing the unsaturated soil behaviour in geo-work constructions. The resulting data should ideally be free and available on the web to serve the engineering community. The author suggests that commercially available finite-element-based software (e.g. GeoStudio, including SIGMA/W for stress and deformation and SEEP/W for groundwater flow) include UNSAT analyses in free student versions. Finally, the learning and teaching material could be used in undergraduate geotechnical engineering courses that are already in place in existing curricula. The additional content would be incorporated into a specific saturated soil mechanic course providing a smooth transition between saturated and unsaturated soil mechanics concepts without changing the workload of the existing curriculum.

5 Concluding remarks

Because soil water saturation conditions vary within wide limits, knowledge in UNSAT SM allows a more realistic geotechnical stability analysis, especially for geo-works constructions subjected to environmental changes. Challenges appear for improving UNSAT SM teaching material that merge smoothly into current undergraduate curricula with flexibility for broad adaptation by educators. Expanding the existing collaborative approaches between members of technical committees of the ISSMGE (i.e., TC 106 and TC 306) with support of regional technical committees could consider developing some short lectures with key principles and concepts and videos with laboratory techniques in unsaturated soils for undergraduate geotechnical engineering courses that could be further explored by local educators. The resulting educational material would help the civil engineering teachers and students to recognise the importance of understanding the hydro-mechanical behaviour of saturated and unsaturated soil conditions in civil engineering practice. The author suggests that experts of the ISSMGE work together with the local educators to develop teaching materials providing a smooth transition between saturated and unsaturated soil mechanics concepts without changing the workload in undergraduate geotechnical engineering classes.

Acknowledgements

The author wishes to thank the Federal University of Espirito Santo, the Brazilian Research Council (CNPq), and the Brazilian Ministry of Education and Culture (MEC-CAPEs) for all their support. The author acknowledges the constructive comments from the anonymous reviewers and the GEE 2025 editors.

References

- Alonso, E. (2012). Unsaturated Soils: Basic Concepts and Applications (Part 1 and Part 2), International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) webinar, <https://www.issmge.org/education/recorded-webinars/unsaturated-soils-basic-concepts-and-applications-part-1-and-part-2>.
- Batali, L., Andreea, C. (2016). Slope stability analysis using the unsaturated stress analysis. Case Study, J. Procedia Engineering 143, pp. 284-291.
- Blight, G.E. (2017). Unsaturated Soil Mechanics in Geotechnical Practice. CRC Press.
- Bicalho, K.V. (2024) Assessment of soil water evaporation using soil surface suction-moisture observations in treated fine-grained soil. Workshop WS 9 cross-linking TCS within the context of Unsaturated Soils. XVIII European Conference on Soil Mechanics and Geotechnical Engineering, Lisbon, Portugal.
- Briaud, J.L. (2013). Geotechnical Engineering: Unsaturated and saturated soils, John Wiley & Sons, Hoboken, NJ.
- Corey, A.T. (1994). Mechanics of immiscible fluids in porous media. Water Resources Publications. Colorado. USA.
- Fredlund, D.G., Morgenstern, N. R., Widger, A. (1978). Shear strength of unsaturated soils. Canadian Geotechnical Journal. 15, pp. 313-321.
- Fredlund, D.G., Rahardjo, H. (1993). Soil Mechanics for Unsaturated Soils in Engineering Practice. John Wiley & Sons.
- Fredlund, D.G. (2019). Unsaturated Soil Mechanics, Chapters 1 through 6, International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) webinar, <https://www.issmge.org/education/virtual-university/unsaturated-soil-mechanics>.
- Gens A., Sánchez M., Sheng D. (2006). On constitutive modelling of unsaturated soils. Acta Geotechnica, 1(3), pp. 137-147.
- Houston S. L. (2024). Unsaturated Soil Mechanics Topics for All Geotechnical Engineers. Indian Geotech J. <https://doi.org/10.1007/s40098-024-01102-5>
- Houston, S.L., Savenye, W., Zapata, C., Ornelas, A. (2014). Introducing Unsaturated Soil Mechanics in the Undergraduate Curriculum, <https://sites.google.com/a/asu.edu/unsaturated-soils-theory-in-undergraduate-civil-engineering-curriculum/home> (accessed Jan. 23, 2020).
- Lehane, B., Ismail, M.A., Fahey, M. (2004). Seasonal dependence of in situ test parameters in sand above the water table. Geotechnique, 54(3), pp. 215-218.
- Leong, E.C., Rahardjo, H., Fredlund, D.G. (2001). Application of unsaturated soil mechanics in geotechnical engineering, The Eighth East Asia-Pacific Conference on Structural Engineering & Construction, EASEC-8, 5-7 December, Singapore.
- Lu, N., Likos, W.J. (2004). Unsaturated Soil Mechanics. Hoboken, New Jersey: John Wiley & Sons Inc.
- Ng, C.W.W., Leung, A.K. (2011). Geotechnical problems and case histories from the perspective of unsaturated soil mechanics, 5th International Conference on Unsaturated soils, 1, pp. 53-90.
- Pantazidou, M., Houston, S., McCartney, J., Tarantino, A., Bardanis, M. (2024). Alert soil mechanics instructors of the main unsaturated soil issues: What and how to teach when experts disagree, 18th European Conference on Soil Mechanics and Geotechnical Engineering, Lisbon, August 26-30.

Tarantino, A., Romero, E., Cui, Y.J. (2005). Advanced Experimental Unsaturated Soil Mechanics: Proceedings of the International Symposium on, EXPERUS 2005. CRC Press.

Tatsuoka, F., Correia, A.G. (2016). Importance of controlling the degree of saturation in soil compaction. Procedia Engineering, 143, pp. 556-565.

Author's bio

Katia Vanessa Bicalho, Federal University of Espirito Santo (UFES) at Vitoria, ES (Brazil)

Dr. Bicalho is a full professor at the UFES who specializes in the field of Geotechnical Engineering. She holds her Civil Engineering degrees from UFES, a master's in civil Engineer of Pontifical Catholic University of Rio de Janeiro, Brazil, and a doctor (Ph. D.) in Civil, Environmental and Architectural Engineering of University of Colorado, Boulder, CO, USA. Her disciplinary research interests involve use of unsaturated compacted soils in civil engineering structures including roadways and earth retaining structures considering soil-atmosphere interactions. She is a member of technical committees of the ISSMGE: TC 106 and TC 306. Due to her geo-engineering teaching interest, she was an invited editor of a special issue in Geo-education in an open access international journal of geotechnical engineering and geoenvironmental engineering, Soils and Rocks, 47 (2), 2024.

Including unsaturated soil concepts in undergraduate courses: The UPC experience

A. Ledesma, E. Romero, P.C. Prat, A. Ramon & N.M. Pinyol

Universitat Politècnica de Catalunya, UPC-BarcelonaTech, Barcelona, Spain

alberto.ledesma@upc.edu, enrique.romero-morales@upc.edu, pere.prat@upc.edu,
anna.ramon@upc.edu, nuria.pinyol@upc.edu

ABSTRACT: The development of Unsaturated Soil Mechanics in the last decades has been spectacular, but mainly in the context of research. There is still a route to go when referring to practical applications or incorporating those concepts in teaching. Many University Departments around the world have participated in research projects contributing to Unsaturated Soil Mechanics, but in general, including the research results in the syllabus of the Civil Engineering curriculum is not straightforward. In fact, it is a topic seldom found in most soil mechanics textbooks. However, the authors believe that the topic is mature enough to be incorporated not only in Master courses, but also in Undergraduate subjects. The paper includes a brief historical perspective of the topic and presents the personal experience of the authors at UPC-BarcelonaTech, trying to include Unsaturated Soil concepts in the subject "Soil Mechanics" of the Civil Engineering Bachelor Degree.

Keywords: Unsaturated Soils, Soil Mechanics syllabus, Undergraduate

1 Introduction

The definition of the contents of a Soil Mechanics course in the context of a Civil Engineering degree seems to be a controversial issue. Indeed, there is no consensus on what to teach at the Undergraduate level and there are sometimes heated arguments on that (Wesley, 2015; Airey & Miao, 2016). The choice depends on external factors as well: how much time ("credits") are available, how many Geo-related subjects are included in the Degree, whether the Degree is professionally oriented or scientifically oriented, what is the previous knowledge of the students enrolled in the subject, etc.

In some countries (as in Spain), the Undergraduate Degree allows one to work at a certain level which is regulated and controlled by a Professional Association. There is no need for an additional examination or any additional license, so when defining the contents of the University courses, it is necessary to keep in mind that. In other countries, however, graduates need to pass an exam from the local Professional Association or must exhibit some guided experience to become a Professional Engineer. In this case, the University has perhaps more freedom to define subject contents.

In addition to those constraints, tradition plays an important role when defining what to teach. Universities have a lot of inertia in managing changes. The current content of the subject "Soil Mechanics" depends a lot on the traditions of each country, including not only technical traditions, but also cultural aspects (Wirth, 2017). In Europe, for instance, and generally speaking, British tradition used to focus on experiments and practical applications, whereas French tradition used to focus on abstract concepts and mathematical developments.

Combining all these conditions, it is possible to understand how each Civil Engineering School or Department defines the content of a Soil Mechanics course. However, some core concepts coincide with most Undergraduate Degrees. The problem arises when new concepts have to be included. Updating the topics to be taught in each subject at the undergraduate level is not obvious, as time is

limited and knowledge is continuously increasing. Including a new topic means that another one has to be excluded. Consequently, changes in the contents of Soil Mechanics courses are limited in time.

In addition to those difficulties, most of the organisations and institutions that have a voice in the improvement of Engineering curricula are not worried about incorporating new, well-established research topics in old syllabuses. On the contrary, they focus on developing particular skills in undergraduate students oriented to their future practical work (Passow & Passow, 2017; Mitchell et al, 2021). Those skills are accepted to be important in a globalised and changing world, but the content itself should be adapted as well to that future. As a matter of fact, the U.S. Accreditation Board for Engineering and Technology (ABET) defined back in 2000 a list of skills that should be acquired for any undergraduate engineering student (Engineering Criteria 2000 or EC2000), which is still a reference (ABET, 2025; Rugarcia et al., 2001). According to ABET Engineering Criteria 2000, future graduates of accredited programs should possess:

- a) An ability to apply knowledge of mathematics, science, and engineering
- b) An ability to design and conduct experiments, as well as analyse and interpret data
- c) An ability to design a system, component, or process to meet desired needs
- d) An ability to function on multidisciplinary teams
- e) An ability to identify, formulate, and solve engineering problems
- f) An understanding of professional and ethical responsibility
- g) An ability to communicate effectively
- h) The broad education necessary to understand the impact of engineering solutions in a global/societal context
- i) A recognition of the need for and an ability to engage in lifelong learning
- j) A knowledge of contemporary issues
- k) An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

Note that these abilities can be accepted as fundamental for an Engineer. However, there is only an indirect reference to the requirement of being at the wedge of the knowledge in the field of expertise (in point -i- referring to lifelong learning). Accreditation bodies are more worried about the rest of the skills, passing almost totally the responsibility of the engineering education to Universities. Probably, they consider that Universities take already care of improving the content of the subjects and they focus on the skills that are more difficult to teach. Nevertheless, many of the skills from the list above can be promoted at Secondary School or acquired while working in a company as a junior engineer. Therefore, the responsibility should be shared, but not assigned to Universities only.

This paper refers to this particular point. It is not about how to promote those skills or how to improve the way we teach. It is about claiming that the content of our subjects should focus on presenting state-of-the-art concepts. The authors strongly believe that it is essential to teach a few fundamental concepts at the undergraduate level, rather than giving too much information on practical applications or techniques that can be acquired at work. There is in fact some consensus on this among academics (Santamarina, 2015). If that approach is assumed, the main concepts related to Unsaturated Soil Mechanics should be included in the teaching material of a Soil Mechanics introductory course. Still, in many Universities, this is not the case yet.

First, a brief historical perspective of the introduction of Unsaturated Soil concepts in Soil Mechanics syllabuses is presented. Then, the particular experience of the authors at UPC is exposed, indicating the contents of the subject and how unsaturated soil concepts are introduced. Finally, some concluding remarks that can be useful in many contexts are indicated.

2 Historical perspective of Unsaturated Soils in Soil Mechanics textbooks

It is broadly accepted that two seminal works in Soil Mechanics, at least from a theoretical point of view, are the book from Terzaghi, "Theoretical Soil Mechanics" (Terzaghi, 1943) and the book from Taylor, "Fundamentals of Soil Mechanics" (Taylor, 1948). Both texts have had much influence on Geotechnical Engineers for decades and still they are highly topical works. An interesting exercise consists on looking at the table of contents of both books with the current perspective. The book by Terzaghi (1943) included the following chapters:

Section A. General principles involved in the theories of Soil Mechanics

- I. Introduction
- II. Conditions for failure in soils
- III. Plastic equilibrium in a semi-infinite mass with a plane surface
- IV. Application of general theories to practical problems
- Section B. Conditions for shear failure in ideal soils
- V. Arching in ideal soils
- VI. Retaining wall problems
- VII. Passive earth pressure
- VIII. Bearing capacity
- IX. Stability of slopes
- X. Earth pressure on temporary supports in cuts, tunnels and shafts
- XI. Anchored bulkheads
- Section C. Mechanical interaction between solid and water in soils
- XII. Effect of seepage on the conditions for equilibrium in ideal sand
- XIII. Theory of consolidation
- XIV. Capillary forces
- XV. Mechanics of drainage
- Section D. Elasticity problems of Soil Mechanics
- XVI. Theories involving a coefficient of subgrade, soil, or pile reaction
- XVII. Theory of semi-infinite elastic solids
- XVIII. Theory of elastic layers and elastic wedges on a rigid base
- XIX. Vibration problems

The table of contents refers to many practical applications like retaining walls, bearing capacity or anchored bulkheads, but includes theoretical concepts as well, such as elasticity and plasticity or the theory of consolidation. It is worth noting the mention of capillarity forces in chapter XIV as a precursor of unsaturated soil concepts. Although that chapter is limited to basic concepts, such as surface tension, capillary rise and gas pressure in bubbles, it is a starting point for unsaturated soil concepts in that seminal work. Nevertheless, no reference to compacted soils is found. The book by Taylor (1948) included the following items in its table of contents:

- 1. Introduction
- 2. Preliminary considerations
- 3. Simple soil tests and classification tests
- 4. Classifications
- 5. Subsurface investigations
- 6. Permeability
- 7. Weights, stresses and heads, seepage forces
- 8. Capillarity
- 9. Seepage
- 10. One-dimensional consolidation
- 11. Use of elastic theory for estimating stresses in soils
- 12. Settlement analysis
- 13. Strength Theory
- 14. Shear testing methods, shearing characteristics of sands
- 15. Shearing strength of cohesive soils
- 16. Stability of slopes
- 17. Lateral pressures, stability of retaining walls
- 18. Soil Mechanics considerations relative to dams
- 19. Action of shallow foundations, bearing capacity
- 20. Action of piles, pile foundations

This book was published 5 years later than Terzaghi's book, but almost simultaneously to the book "Soil Mechanics in Engineering Practice", by Terzaghi & Peck (1948), oriented to Geotechnical Engineers and as a complement of the initial book "Theoretical Soil Mechanics".

The book by Taylor (1948) has an academic perspective, typical of a textbook of an Engineering degree. The adjective "Fundamentals" is appropriate, considering its content. Note that there is a chapter on Capillarity, where concepts such as surface tension and capillary pressure are introduced. The concept

of “capillary pressure” used by Taylor and still used nowadays, is similar to the idea of “capillary force” described in the book by Terzaghi. Again, no reference to compacted soils was made.

It is important to mention that both books constitute a visionary work, including the core topics of a typical Soil Mechanics course. Obviously, after 80 years, language and some of the procedures have evolved, but many of the concepts remain. Despite that, it is not acceptable to teach Soil Mechanics today considering the topics covered by those books only. It is necessary to incorporate part of the concepts developed up to today to have a modern vision of Soil Mechanics.

Hence, the concept of capillarity presented in Terzaghi (1943) and Taylor (1948) must be included and developed in a modern manner in current courses. Surprisingly, many textbooks published later did not include the concept of capillary pressure, and capillarity was, for many years, an anecdotic issue.

As a matter of fact, the book by Lambe & Whitman (1969), used in several Universities as a textbook and translated into several languages, did not include any reference to capillarity or soil compaction: the book has a section on dry soil and a section on saturated soil behaviour. However, it is now recognised that the critical behavioural features of unsaturated soil occur while undergoing hydraulic changes. The reference to capillarity is very heterogeneous depending on the country and local tradition. A Russian textbook published back in 1963, revised in 1973, and published in English in 1976 devotes just one line to the idea of capillarity (Tsytoich, 1976). The textbook by Atkinson, “An introduction to The Mechanics of Soils and Foundations: through Critical State Soil Mechanics” (1993) presented a single paragraph about the water pressure above the water table, and justified not including a section on unsaturated soils because “... major civil engineering structures are usually saturated, at least in temperate or wet climates”. Another popular book in UK, the textbook by Craig, includes in its 7th edition (2004) a few lines about capillarity and one page extending the concept of effective stress to unsaturated conditions (Craig, 2004).

A group of textbooks present concepts related to unsaturated soils from the point of view of applications. For instance, the “Textbook of Soil Mechanics and Foundation Engineering” by Murthy (2017) from India, includes a chapter on capillarity, but also develops an additional chapter on collapsible and expansive soils, an applied topic related to unsaturated conditions. It is also the case of the classical book by Smith in its 10th edition (2021), where a section on capillarity and unsaturated soils is complemented by a section on soil compaction.

In some areas where unsaturated soils are very common, the table of contents of textbooks reflected that condition. In Mexico, the book by Juárez-Badillo & Rico-Rodríguez (3rd edition 1998) includes a chapter on capillarity and shrinkage after desiccation, a section on unsaturated shear strength and a chapter on compaction. In Spain, the book by Jiménez-Salas & Justo-Alpañes (1975) develops the concept of capillarity and surface tension, and includes a chapter on soil compaction and another chapter on shear strength of unsaturated soils.

Then, it is possible to observe an evolution of the table of contents of the textbooks, although from a global perspective, it is unequal and heterogeneous. Sometimes, that depends on the target readers of the book, either undergraduate or graduate students. Simultaneously, research on the topic was growing, and there was a considerable development of Unsaturated Soil Mechanics at the end of 20th century.

Following the publication of several books on unsaturated soils, ranging from the seminal work by Fredlund and Rahardjo (1993) to Blight (2013) and Ng et al. (2025), Jean-Louis Briaud's book, “Geotechnical Engineering: Unsaturated and Saturated Soils”, first published in 2013, offers a joint perspective on the behaviour of both saturated and unsaturated soils.

In 1987, the 9th European Conference on Soil Mechanics and Foundation Engineering was held in Dublin (Ireland). There was a session on “Special Problem Soils” and the general report was prepared by Alonso, Gens & Hight (1987). In that Conference, those soils included partially saturated soils, and very soft and organic soils. The general report presented both types of soils in separate sections, due to the disparity of their properties and casuistry. It should be pointed out that at that time, unsaturated soils where “special soils”, so not very important in the context of the whole Conference. The authors claimed that unsaturated soils should be “normal soils”, as unsaturation is a condition not related to the type of soil.

Since the first book on unsaturated soils was published, a series of conferences have been held on this topic, such as the 1st International Conference on Unsaturated Soils in Paris (Alonso & Delage, 1995)

followed by the regional conferences 1st Asian Conference on Unsaturated Soils in Singapore (Rahardjo et al., 2000) and the 1st European Conference on Unsaturated Soils in Durham UK (Toll et al., 2008).

There is no doubt that nowadays, Unsaturated Soils is a well-established discipline within Soil Mechanics and is the topic of a Technical Committee (TC106) within the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE, 2025). That Committee belongs to the category “Fundamentals”, as the Committees on “Laboratory Stress Strain Strength Testing of Geomaterials”, “Ground Property Characterization from In-Situ Tests”, “Numerical Methods”, “Physical Modelling in Geotechnics”, “Geo-mechanics from micro to macro” and “Tropical Residual Soils”. Note that most of the names of “Fundamental Committees” correspond to well-established topics in the Soil Mechanics curriculum. However, the topic “Unsaturated Soils” is still missing in many Soil Mechanics courses.

3 The experience at UPC

3.1 Introducing Soil Mechanics to undergraduate students

The Geotechnical Group at UPC (Universitat Politècnica de Catalunya-BarcelonaTech) participates in the teaching tasks at the Civil Engineering School of Barcelona (Spain) contributing to the Undergraduate and Master Civil Engineering degrees. The Master degree leads to the traditional professional Spanish title of “Ingeniero de Caminos, Canales y Puertos” (roads, canals and ports engineer). The group offers a specific Master degree in Geotechnical Engineering as well.

The subjects of the Civil Engineering Bachelor degree related to the topic of this paper are Applied Geology (year 1, 6 credits), Groundwater hydrology (year 3, 3 credits), Geotechnics (year 3, 6 credits) and Geotechnical Engineering (year 4, 4.5 credits) (Camins-UPC, 2025). Each credit corresponds to the European Credit Transfer System definition (ECTS, 2025) and typically involves 10 hours of lecturing. Here, details of the subject Geotechnics are described, where the fundamental Soil Mechanics concepts are introduced to students. The subject of Geotechnical Engineering develops conventional applications, such as field investigation, retaining walls and shallow and deep foundations.

The content of the course Geotechnics has been quite constant in the last 10 years, although the order of the units has been changed recently. The original order included the chapter on flow in porous media at the beginning of the course; now, thanks to the coordination with the subject of Groundwater hydrology, which is simultaneous to Geotechnics, the size of that unit has been reduced and moved towards the end of the course (OCW Camins, 2025). In this manner, it is possible to focus on the mechanical concepts, which are particularly difficult for the students to understand. The “Soil Mechanics film” is presented at the beginning, that is, the fact that loading a saturated soil implies that part of the load is transferred to water pressure, and then some water moves away (the water volume allowing for deformation), leaving the soil saturated. This time-dependent problem is simplified in classical Soil Mechanics considering short-term (undrained) and long-term (drained) conditions, substituting the whole film with two essential fixed pictures. This phenomenon can be explained by a very simple geometry (a horizontal saturated soil layer).

The units currently taught are listed below. For each unit, the number of hours for Theory lectures (T), Problem-solving lectures (P) and Laboratory sessions (L) is indicated as well.

First part:

0. Introduction. Examples of geotechnical problems. Organisation of the course. (2T)
1. Soil Characterization. Soil phases and soil structure. Grain size distribution. Consistency, Atterberg limits, Plasticity chart. Classification of soils. (3T, 1P, 2L)
2. Fundamental concepts. Stresses and strains, invariants. Mohr circle. Total and Effective stresses. Lambe and Cambridge representations. Stress paths. Concepts of elasticity and plasticity. Elastic solutions. (6T, 2P)
3. Experimental behaviour of soils. Triaxial test. Oedometer test. Shear tests. Experimental behaviour of sands and clays. (6T, 2P)
4. Unsaturated soils and compacted soils. Surface tension and capillary rise. Effect of suction on unsaturated soils (volume changes on wetting and drying). Compacted soils, micro and macro-structure. Proctor test. (2T, 2L)

Partial Assessment (3 hours exam)

Second part:

5. Stress-strain-strength behaviour. The Cam-clay model. Mohr-Coulomb shear strength. Undrained shear strength. Limit equilibrium. Slope stability problems. (8T, 6P)
6. Flow in saturated and non-deformable soil. Hydraulic head. Darcy's law and water balance equation. Seepage forces, critical gradient and liquefaction. Flow problems, graphical method. (6T, 4P, 2L)
7. Consolidation of saturated soils. One-dimensional theory of consolidation. Dimensionless approach. Consolidation due to piezometric changes. Degree of consolidation. Radial flow and vertical drains. (4T, 2P)

Final assessment (3 hours exam)

The units include not only theoretical lectures, but also solving exercises and performing laboratory experiments. This is combined with optional homework exercises (one exercise for each topic is graded individually and is used in the final assessment of students).

Laboratory sessions involve small groups, typically of 16 to 20 students. They have to prepare a report individually for each session that is graded. The total number of students following the subject is about 150, so only 3 laboratory sessions are planned consisting of:

- L1. Soil identification. Consistency. Students have several samples of soils (sand, low plasticity and high plasticity clay, non-uniform soils...) and have to classify using simple techniques (texture, grain size, effect of water, etc.).
- L2. Compacted soils. Students perform a "mini-Proctor" compaction test using soil from the campus at different water contents. Samples compacted on the dry side collapse when wetting. A visit to the main lab to see triaxial, oedometer and shear devices is included. Only the students at Master or PhD level use these devices.
- L3. Flow of water. In a permeameter, students perform a constant head test and a falling head test. By changing the gradient, they have to induce liquefaction.

3.2 Introducing Unsaturated Soil Mechanics

At UPC, there is a long tradition of studying unsaturated soils since the creation of the Civil Engineering School back in 1974. The initial paper by Lloret and Alonso (1980) is a consequence of that. Soon, the research developments were incorporated into the undergraduate and graduate course contents. Updating the syllabus to consider the developments in the field is an essential responsibility of academics, because research and teaching are closely related.

Unsaturated soils are common in Mediterranean climates, and compacted soils are also unsaturated. Compaction was taught in specific subjects on Transportation or Road construction, based on empiricism and without a Soil Mechanics perspective. Including the conceptual aspects of Compaction in the Soil Mechanics syllabus was a fundamental achievement.

In the units mentioned in section 3.1, unsaturated soils are present in several sections. Unit 1 about soil characterisation includes the description of the soil phases, the concept of water content and the degree of saturation. Consistency limits include shrinkage limit due to desiccating conditions. In unit 2, the concepts of water pressure and effective stress are presented. That poses the question of what is the water pressure above water table, a point that is explained in detail in unit 4. Unit 3 focuses on laboratory mechanical experiments of saturated soils and presents the typical results obtained in those experiments carried out on sands (loose and dense) and clays (normally and overconsolidated).

Unit 4 is entirely devoted to unsaturated soils. This includes teaching the concept of suction, retention curve and the properties of unsaturated soils, in terms of permeability and strength (in a qualitative manner, as mechanical models have not been presented yet). The unit includes conceptual aspects of compaction as well, that is, the Proctor test related to the effect of suction, and the soil microstructure generated depending on the water content conditions (dry and wet sides of the curve). A quite frequent defect in embankments in dry climates is the collapse of the compacted soil after heavy rain and subsequent saturation (Alonso et al., 2010). Therefore, the course includes a laboratory session based on this phenomenon. To speed up that session, students use a small version of the Proctor cylindrical mould designed at UPC. It is possible to apply a vertical load and to add water, so eventually, the swelling of very dense samples or the collapse of low density samples can be shown straightforwardly. The importance of the total stress changes on the one side, and the water content changes on the other side, points out that both variables control unsaturated soil behaviour, and brings attention to the lack of

an “effective stress”, as in saturated soils. Figure 1 shows some sketches used in the presentations, referring to fundamental concepts, as capillary rise, suction and its mechanical effect on strength and water retention properties. In addition to that, photographs of compaction works are shown to the students as well.

Unit 5 is the central topic of the subject and refers to the mechanical behaviour of soils, particularly clays. The critical state concept and the Cam-clay model are presented. We consider it fundamental to teach undergraduate students the main concepts of plasticity, and the Cam-clay model is the most straightforward framework available to present those concepts. A simple version is introduced, focussing on qualitative behaviour rather than on the numerical expressions. It is fundamental to understand the drained and undrained behaviour of normally and overconsolidated clays, and to relate the model predictions with the experimental results presented in unit 3. The Mohr-Coulomb strength criterion and the undrained shear strength concept follow. However, they are presented critically, highlighting their limitations and misuse (Ledesma, 2024). The strength of unsaturated soils is not taught at the undergraduate level, but at a Master level, due to the available time, since students know qualitatively that suction tends to increase the shear strength.

Unit 6 and 7 refer to saturated soils only. Unit 6 introduces the classical content of flow in saturated porous media, taking into account that students have already followed a short course on Groundwater Hydrology. Therefore, the focus is on the mechanical aspects, as seepage forces, critical gradient, liquefaction phenomena and the uplift risk in excavations. Finally, unit 7 presents the classical theory of consolidation, although the word consolidation has already been introduced to students in unit 3, when introducing the triaxial test. This topic was presented earlier in a previous version of the syllabus. It is reasonable to explain the concept of consolidation at the beginning and leave the mathematical theory to a final unit of the course.

The experience of the last 10 years with this organization is reasonably good, but there are also some drawbacks. In particular, the course, as defined above, is quite intense, and the feedback from the students reveals that it includes too many new concepts for a semester, and a quarter of students have

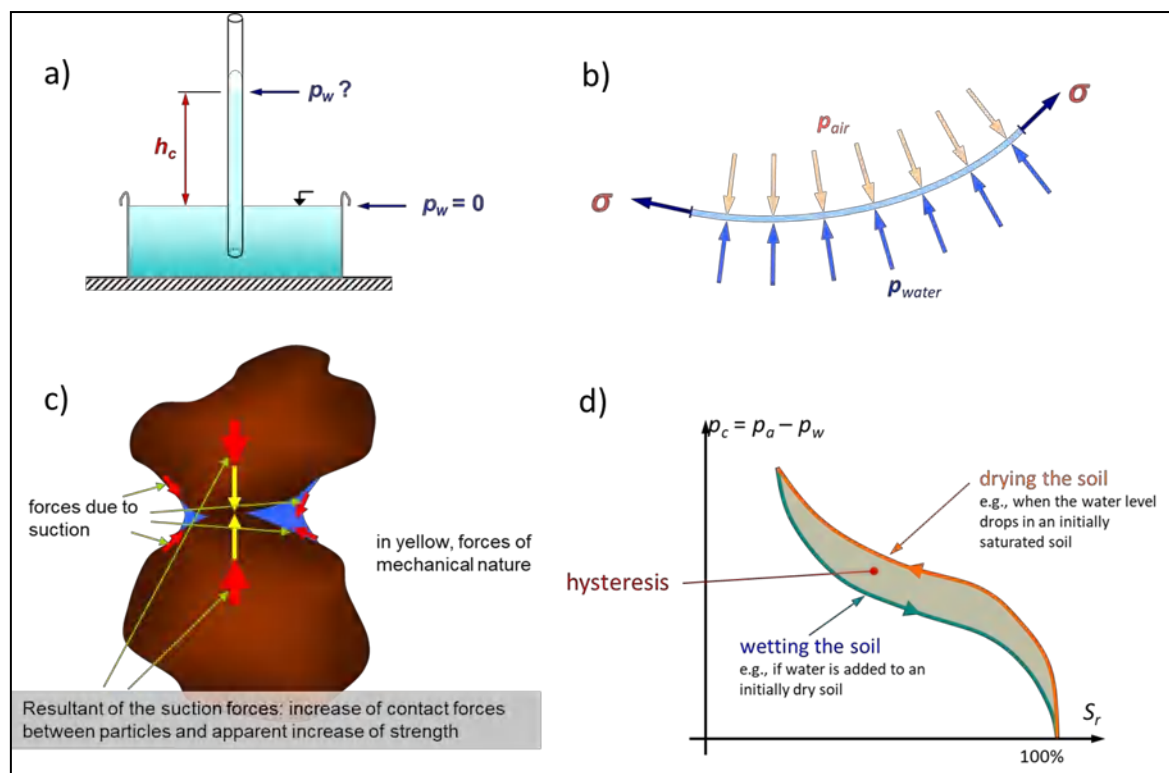


Figure 1. Sketches used in lecture notes: a) capillary rise h_c and zero water pressure; b) surface tension concept, σ ($p_{air} > p_{water}$); c) mechanical effect of suction; d) soil water characteristic curve or retention curve (suction or capillary pressure, p_c , against Saturation degree, S_r)

difficulty passing the course within a year. This is not a good rate for a subject in 3rd year of the Bachelor Degree, considering that the more selective subjects are the mathematical courses located in 1st and 2nd years. This is another debate related to the admissions of new students at the Bachelor Degree, and to the decreasing interest on Civil Engineering from young people in the last decade, at least in Spain.

4 Concluding remarks

This paper presents a view of the incorporation of Unsaturated Soil Mechanics concepts in the syllabus of an introductory Soil Mechanics course at the undergraduate level. The authors believe that academics are responsible for updating the contents of the courses, including the state-of-the-art of the discipline. In this manner, teaching is enriched by research. From that perspective, a minimum content on Unsaturated Soils, a topic mature enough nowadays, should be included in this type of course. This task is not easy, as including new content usually means that other material must be excluded.

The particular experience of the authors at UPC-BarcelonaTech is shown in the paper. There are probably site-dependent constraints, but we think that it is possible to present a Soil Mechanics introductory course including modern concepts as Critical State Soil Mechanics and Unsaturated Soils. Including Unsaturated Soil concepts has been a fundamental issue for engineers who work in a Mediterranean climate context, where the water table is generally not close to the surface. In addition to that, it is also a global requirement for engineers dealing with the construction of embankments, or when looking at Civil Engineering as a global profession in a global world, so even professionals educated in wet climates may work in dry areas. In this context, climate change will be a challenge that has to be faced with the incorporation of topics as unsaturated soil behaviour in our courses.

References

- ABET (2025). Accreditation Board for Engineering and Technology. <https://www.abet.org>, access 15th January 2025
- Airey, D., Miao, G. (2016). Why Critical State Soil Mechanics should be taught to all civil engineers. Shaping the Future of Geotechnical Education: International Conference on Geo-Engineering Education – TC-306. SFGE-2016. Belo Horizonte, Brazil
- Alonso, E.E., Delage, P. (1995). Proc. 1st International Conference on Unsaturated Soils, UNSAT'95, Paris. A.A. Balkema, Rotterdam.
- Alonso, E.E., Pinyol, N.M., Puzrin, A.M. (2010). Collapse of Compacted Soil: Girona Road Embankments, Spain. In Geomechanics of Failures. Advanced Topics. Springer, Dordrecht.
- Alonso, E.E., Gens, A., Hight, D.W. (1987). General Report. Groundwater effects in Geotechnical Engineering: Proc. Of the 9th European Conference on Soil Mechanics and Foundation Engineering, Hanrahan E.T., Orr, T.L.L., Widdis, T.F., vol. 3, pp. 1087- 1146. Dublin. A.A. Balkema, Rotterdam.
- Atkinson, J. (1993). An Introduction to the Mechanics of Soils and Foundations: through Critical State Soil Mechanics. McGraw Hill, London, UK.
- Blight, G.E. (2013). Unsaturated Soil Mechanics in Geotechnical Practice. CRC Press Taylor & Francis Group, Boca Raton, USA.
- Briaud, J.L. (2013). Geotechnical Engineering: Unsaturated and Saturated Soils. John Wiley & Sons, Hoboken NJ, USA.
- Camins-UPC (2025). Plan of the Civil Engineering Degree, School of Civil Engineering at Barcelona (Spain). https://camins.upc.edu/en/Studies/bachelor/civil-engng-20/civil-engng?set_language=en, access 22nd January 2025.
- Craig, R.F. (2004). Craig's Soil Mechanics. 7th edition. Spon Press, London, UK.
- ECTS (2025). European Credit Transfer System. <https://education.ec.europa.eu/education-levels/higher-education/inclusive-and-connected-higher-education/european-credit-transfer-and-accumulation-system>, access 22nd January 2025.

- Fredlund, D.G., Rahardjo, H. (1993). *Soil Mechanics for Unsaturated Soils*, John Wiley & Sons, New York, USA.
- ISSMGE (2025). International Society for Soil Mechanics and Geotechnical Engineering. <https://www.issmge.org/committees/technical-committees>, access 16th January 2025.
- Jiménez-Salas, J.A., Justo-Alpañes, J.L. (1975). *Geotecnia y Cimientos – I, Propiedades de los Suelos y las Rocas*. 2nd edition, Ed. Rueda, Madrid, Spain.
- Juárez-Badillo, E., Rico-Rodríguez, A. (1998). *Mecánica de Suelos – vol 1, Fundamentos de la Mecánica de Suelos*. 3rd edition, Ed. Limusa, México D.F.
- Lambe, T.W., Whitman, R.V. (1969). *Soil Mechanics*, John Wiley & Sons, New York, USA.
- Ledesma, A. (2024). The difficult task of teaching shear strength of soils. *Soils and Rocks*, 47(2), e2024003424.
- Lloret, A., Alonso, E.E. (1980). Consolidation of unsaturated soils including swelling and collapse behavior. *Géotechnique*, 30(4), pp. 449-477.
- Mitchell, J.E., Nyamapfene, A., Roach, K., Tilley, E. (2021). Faculty wide curriculum reform: the integrated engineering programme. *European Journal of Engineering Education*, 46(1), pp. 48-66.
- Murthy V.N.S. (2017). *Textbook of Soil Mechanics and Foundation Engineering*. CBS Publishers, New Delhi, India.
- Ng, C.W.W., Zhou, C., Ni, J. (2025). *Advanced Unsaturated Soil Mechanics. Theory and Applications*. 2nd edition. CRC Press Taylor & Francis Group, Abingdon, UK.
- OCW Camins (2025). Open Course Ware from School of Civil Engineering at UPC. <https://ocw.camins.upc.edu/ocw/assignatura/2500020/2024/temari>, access 22nd January 2025.
- Passow, H.J., Passow, C.H. (2017). What competencies should undergraduate engineering programs emphasize? A systematic review. *Journal of Engineering Education*, 106(3), pp. 475-526.
- Rahardjo, H., Toll, D.G., Leong, E.C. (2000). *Unsaturated Soils for Asia*. Proc. of the 1st Asian Conference on Unsaturated Soils, Singapore, A.A. Balkema, Rotterdam.
- Rugarcia, A., Felder, R.M., Woods, D.R., Stice, J.E. (2000). The Future of Engineering Education. Part 1: A vision for a new century. *American Society for Engineering Education – Chemical Engineering Education Journal*, 34(1) pp. 16-25.
- Santamarina, J.C. (2015). (What) to teach or not to teach – that is the question. *Geotechnical Research*, 2 (4), pp. 135-138.
- Smith, I. (2021). *Elements of Soil Mechanics*. 10th edition. Wiley-Blackwell.
- Taylor, D.W. (1948). *Fundamentals of Soil Mechanics*, John Wiley & Sons, New York, USA.
- Terzaghi, K. (1943). *Theoretical Soil Mechanics*, John Wiley & Sons, New York, USA.
- Terzaghi, K., Peck, R.B. (1948). *Soil Mechanics in Engineering Practice*, John Wiley & Sons, New York, USA.
- Toll, D.G., Augarde, C.E., Gallipoli, D., Wheeler, S.J. (2008). *Unsaturated Soils. Advances in Geo-Engineering: Proc. of the 1st European Conference, E-UNSAT 2008, Durham (UK)*, CRC Press.
- Tsytoich, N. (1976). *Soil Mechanics*. Mir Publishers, Moscow.
- Wesley, L. (2015). (What) To teach or not to teach – from theory to practice. *Geotechnical Research*, 2 (4), pp. 139-147.
- Wirth, X., da Silva, T., Della Vecchia, G., Evans, J., Romero, E., Bhatia, S.K. (2017). Undergraduate Geotechnical Engineering Education of the 21st Century. *Journal of Professional Issues in Engineering Education and Practice*, ASCE 143(3), pp. 1-8.

Authors' bios

Alberto Ledesma, Universitat Politècnica de Catalunya – BarcelonaTech, (Spain)

Dr. Alberto Ledesma is a Full Professor of Soil Mechanics and Geotechnical Engineering at UPC since 2002. He has developed his research work in basic areas such as inverse analysis, finite elements applied to geotechnical problems (including dynamics) and unsaturated soils, particularly the analysis of shrinkage and cracking in desiccating soils. In more applied aspects, his work stands out in the study of landslides, the design of engineering barriers for the storage of radioactive waste and the design of tunnels in urban areas, leading projects at National and European level. His teaching experience includes subjects as Soil Mechanics at undergraduate level and Soil Dynamics and Numerical Models in Geotechnical Engineering at Master level. He is committed to improving the teaching of Soil Mechanics, particularly when presenting fundamental concepts to undergraduates. He belongs to ISSMGE Technical Committee TC-306 on Geo-engineering Education since 2008. His contributions on that include the use of ICT (i.e. virtual lab to teach Cam-clay model) and the development of digital twins of laboratory tests.

Enrique Romero, Universitat Politècnica de Catalunya – BarcelonaTech, (Spain)

Enrique Romero is a Full Professor and Head of the Geotechnical Laboratory at UPC. His research primarily focuses on experimental and theoretical studies of multi-physics and multi-scale processes in soils and rocks. He has served as PI for Europe/America/Asia mobility programmes for researchers, Marie Curie Innovative Training Networks, alongside Spanish industrial and knowledge generation initiatives. He has co-organised several international Doctoral Schools dedicated to experimental soil mechanics within the European ALERT Geomaterials network, and he has co-edited the books 'Advanced Experimental Unsaturated Soil Mechanics' (2005), 'Laboratory and Field Testing of Unsaturated Soils' (2009), and 'Advanced Experimental Techniques in Geomechanics' (2012). He has supervised twenty-three doctoral theses on experimental soil mechanics and geotechnical applications. He chairs TC 106 ISSMGE of Unsaturated Soils. His teaching experience has covered subjects at both undergraduate and master's levels, encompassing a wide range of topics, including soil mechanics and foundations, strength of materials, offshore foundations, and marine geodynamics. He is dedicated to enhancing teaching by incorporating experimental soil mechanics and physical models to aid the understanding of fundamental and applied concepts.

Pere C. Prat, Universitat Politècnica de Catalunya – BarcelonaTech, (Spain)

Dr. Pere Prat is an Associate Professor at the Technical University of Catalonia (UPC), Barcelona, Spain, who specializes in Soil Mechanics. He holds his Civil Engineering degrees from UPC-Barcelona and Northwestern University, USA. His main research interests are in the field of geotechnical engineering, localization and cracking, cracking in drying soils, constitutive models for geomaterials, numerical methods applied to geotechnical engineering and coupled problems. In recent years, Dr. Prat has been involved in the development of new methodologies for teaching Soil Mechanics to undergraduate students, proposing mechanisms and activities that have encouraged students' interest in learning the subject through their active participation in the academic activities. His current teaching research involves the creation of small prototypes for conducting experiments in class illustrating some key concepts of Soil Mechanics that act as catalysts and fixers of the subject-specific competencies as well as developing digital twins of the physical experiments.

Anna Ramon, Universitat Politècnica de Catalunya – BarcelonaTech, (Spain)

Dr Anna Ramon Tarragona is an Associate Professor at the Technical University of Catalonia (UPC), Barcelona, Spain. She develops research and teaching activity at the Department of Civil and Environmental Engineering of UPC and at the International Centre for Numerical Methods in Engineering (CIMNE). She also works as a consultant for contractors, public institutions, designers and builders. She has experience in laboratory, in-situ investigation, field monitoring and numerical modelling research. Her research and professional dedication focus on the study of the expansive behavior in anhydritic rocks and cement treated compacted soils, and its interaction with underground excavations,

foundations and embankments; the development of numerical models to describe thermo-hydro-mechanical and chemical coupled processes and the application of them for the simulation of geotechnical problems. She teaches at Undergraduate and Master levels in courses related to Geotechnics, Tunneling, Scientific and technical communication, Environmental impacts generated by infrastructures and Environmental legislation; she publishes chapters on practical applications in text books and lectured professional courses. She also contributes to training of young researchers through the direction of Degree, Master and PhD Thesis.

Núria M. Pinyol, Universitat Politècnica de Catalunya – BarcelonaTech, (Spain)

Dr Núria M. Pinyol is Associate Professor in the Department of Geotechnical Engineering at Universitat Politècnica de Catalunya (UPC). Her research focuses on thermo-hydro-mechanical couplings in porous media from a theoretical, numerical and experimental point of view. She started as an Assistant professor in 2010 after finishing her PhD providing support on Master Courses on Underground Excavation. Nowadays, she is also professor on Soils Mechanics and Geotechnics in both undergraduate and master courses. She is co-author of two original books published in Springer entitled “Geomechanics of Failures” and “Geomechanics of Failures. Advanced Topics”. Since 2013, she is responsible of a course based on these two books incorporated in the UPC Master in Civil Engineering and in the specialized UPC Master on Geotechnical Engineering. She also gives part of this course in other centers in an intensive-course format. She also participated in specialized courses on specific topics (i.e. constitutive modelling, unsaturated soils, numerical modelling, and training courses codes).

Teaching unsaturated seepage and wetting-collapse coupled modelling

N.M. Pinyol^{1,2} & E.E. Alonso^{1,2}

¹*Civil and Environmental Engineering, Universitat Politècnica de Catalunya, Barcelona, Spain*

²*Centre Internacional de Mètodes Numèrics en Enginyeria (CIMNE), Barcelona, Spain*
nuria.pinyol@upc.edu, eduardo.alonso@upc.edu

ABSTRACT: When teaching unsaturated soil mechanics, the behaviour of the soil is often described by distinguishing the effect of non-saturation on seepage and, in an independent manner, the effect of suction on mechanical behaviour, highlighting the strength and volume changes. The coupled hydro-mechanical behaviour is a step forward that is commonly addressed by elaborating the theoretical fundamentals (balance equations). The application to real cases is solved numerically presenting the results obtained by computational tools (i.e. Finite element-based codes). In the authors' experience, the students have a knowledge gap between the constitutive models describing the hydraulic and mechanical soil behaviour and their coupling required to solve engineering problems. This paper presents the modelling of seepage and wetting-induced volumetric collapse by defining a simplified plastic constitutive model that neglects the elastic regime. These assumptions maintain fundamental aspects of non-saturated soils. The governing equation is finally applied to a case history of a road embankment that exhibited a pronounced volume loss after rainfall, damaging road structures.

Keywords: Unsaturated soils, Collapse, Analytical solution, Hydro-mechanical coupling, Case history

1 Introduction and purpose of the paper

This paper has two goals: 1) To help and teach the students to develop skills to formulate by themselves models adapted to a particular problem and 2) To attract their attention by connecting the learning experience described in sections 3 to 5 of the paper to the unexpected performance of a geotechnical structure (in our case, a significant embankment collapse).

The behaviour of unsaturated soils is critically dependent on stress and water content changes. Two distinct features of behaviour, collapse and swelling, can only be understood by a joint consideration of stress and suction changes. The implication, when dealing with field applications, is that hydraulic and mechanical response should be jointly considered. The key point is that the two phenomena are highly coupled.

There are some teaching difficulties to fully understand the process leading to modelling real cases such as the behaviour of embankments, earth dams, or foundations on unsaturated soils.

For a long time now, a general formulation for the coupled behaviour of unsaturated soils has been available: the "mechanical" response requires equilibrium (momentum balance) of soil constituents (liquid, gas, and soil mixture) and the flow-related behaviour derives from the condition of mass balance (conservation) of phases (solid, liquid and air). Constitutive relations complete the formulation.

The path beyond this point is lost by many students because it requires an effort to follow the building of an elaborated numerical model, typically based on finite element formulations.

This paper describes the intermediate steps to find a workable solution of a simplified, but useful approach, that provides a solution applicable to real field cases. This is done by introducing some simplifications, but the fundamentals of the coupled formulation are preserved.

The real case behind this paper is the rainfall induced collapse observed in a road embankment to access a bridge abutment (Figure 1). The road authority wanted an explanation for the observed displacement and, also, an evaluation of the remaining collapse potential in case of future rainfall.



Figure 1. Rainfall induced collapse of a bridge abutment. Note that the embankment settled and deformed horizontally

The paper is organized as follow. (1) Formulation of balance equations adopted for a one-dimensional (isotropic) case; (2) Description of a simplified constitutive model for collapse phenomenally; (3) Additional necessary constitutive relations; (4) Derivation of the integrated partial differential equation describing the coupled phenomenon and; (5) Applications to the field case.

This sequence of steps follows a logical order: To start, the basic physical phenomena are identified: mass balance relationships and mechanical equilibrium. The equilibrium will be simplified to an elementary exercise (the calculation of stresses in a constrained column of soil of varying unit weight). This simplification has some sense because we are dealing with an embankment case and investigating the behaviour of its central part will be a reasonable choice if the purpose of the analysis is to determine rain-induced collapse settlements. The second step is a required information in this case: how was collapse defined in mathematical terms? A simple plastic model was developed to show how to do it. The third step collects well known flow-related constitutive models. The fourth one is a key step: It shows how to integrate basic principles and constitutive relations into a solvable partial differential equation, at a limited effort.

2 Balance equations

In this Section the required mass balance relationships, in differential form, are first presented in its general formulation and, when needed, adapted to the 1D dimension of the problem

The gas pressure will be assumed to be a reference (zero) constant pressure. Gas density will also be assumed constant. Under these assumptions there is no need to introduce a balance equation for gas flow. Two mass conservation conditions remain for the solid and liquid phases. The local expression for the solid mass conservation is:

$$\frac{\partial}{\partial t}[(1-n)\rho_s] + \mathbf{div}[\rho_s(1-n)\mathbf{v}] = 0 \quad (1)$$

where ρ_s is the density of soil grains, n the porosity and $(1-n)$ the volume filled by solid particle per unit volume of soil, and $\mathbf{v}$ the veloc

ity of solid grains. The first term in Eq. (1) is the rate of change of solid mass in a unit volume having a porosity n , and the second is the flow rate of solid mass entering or leaving the unit volume at a velocity $\mathbf{v}$. Expanding the terms of Eq. (1) and introducing the definition of the material derivative ($\frac{D(\cdot)}{Dt} = \frac{\partial(\cdot)}{\partial t} + \mathbf{v} \cdot \mathbf{grad}(\cdot)$), Eq. (2) is obtained

$$\frac{Dn}{Dt} = \frac{(1-n)}{\rho_s} \frac{D\rho_s}{Dt} + (1-n)\mathbf{div}(\mathbf{v}) \quad (2)$$

Accepting that the compressibility of the soil skeleton is large compared with the compressibility of grains, Eq. (2) becomes:

$$\frac{Dn}{Dt} = -(1-n) \frac{\partial \varepsilon_{vol}}{\partial t} \quad (3)$$

where ε_{vol} , the volumetric deformation (compression is assumed positive) defined in terms of the divergence of the solid displacements, $\mathbf{v}$, has been introduced ($\mathbf{div}(\mathbf{v}) = \mathbf{div}\left(\frac{\partial \mathbf{u}}{\partial t}\right) = \frac{\partial}{\partial t} \mathbf{div}(\mathbf{u}) = -\frac{\partial \varepsilon_{vol}}{\partial t}$).

The local expression for the water balance follows directly from equation (1) by formally replacing $(1-n)$ by the volume filled by liquid per unit volume of soil, nS_r , the solid density, ρ_s by ρ_w , and $(1-n)\mathbf{v}$ by $(nS_r\mathbf{v} + \mathbf{q})$, where $\mathbf{q}$ is the Darcy flow in an unsaturated soil:

$$\frac{\partial}{\partial t}[nS_r\rho_s] + \mathbf{div}[\rho_w(nS_r\mathbf{v} + \mathbf{q})] = 0 \quad (4)$$

As done previously with the solid mass balance equation, Eq. (4) can be expanded and the definition of the material derivative introduced. The compressibility of the water can be neglected, and equation (3) invoked, resulting in:

$$n \frac{\partial S_r}{\partial t} - S_r \frac{\partial \varepsilon_{vol}}{\partial t} + \mathbf{div}(\mathbf{q}) = 0 \quad (5)$$

where the definition of volumetric strains is used.

Notice that Eq. (5) corresponds to the mass balance including solid and liquid since equation (3) is considered.

Eq. (5) can be easily interpreted: the two first terms describe the change of water stored in a unit volume due to changes in degree of saturation or changes in void volume. This changes in water stored is compensated by a water flow rate (third term).

So far, no mention is made to the equilibrium conditions. The volumetric deformation in equation (5) will be controlled by stresses and suction. The calculation of stresses is straightforward if the real case to be solved is simplified as a column of soil. Figure 2 illustrates the case. The objective will be to calculate the settlement of a central column of the collapsing embankment. Vertical stresses at any point of the column depend on the soil unit weight. A mean confining stress is obtained if a K_0 coefficient is assumed (in our case $K_0 = 0.5$). But the volumetric strains upon wetting require a constitutive model.

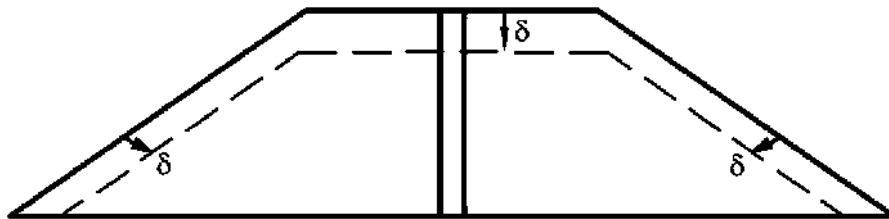


Figure 2. Two-dimensional section of the embankment and central column selected for the analysis under one-dimensional conditions. The effect of volumetric collapse is schematized

3 Constitutive model for collapse strains

The model adopted is a simplification of the BBM (Alonso et al., 1987, 1990). Since collapse strains dominate the observed field behaviour, the idea was to disregard elastic strains and to concentrate on the Loading Collapse (LC) yield surface for isotropic stress states (see the definition below). The LC is formulated in terms of two independent constitutive stresses: total mean stress, p , and suction, s . This is a useful choice to interpret laboratory tests and to integrate the constitutive model into the balance equation (5).

In BBM, the equation of the yield surface in a (p,s) stress plane was derived by assuming a stress-strain behaviour under isotropic loading-unloading stress paths, very much inspired in the common interpretation of oedometer test results of soils. This procedure leads to a direct relationship between the parameters of the LC yield curve and the parameters describing the test results (i.e.: virgin compressibility and elastic parameters against suction and stress changes). However, there are other alternatives: finding an expression for the yield locus by assuming a particular expression for the internal dissipation of energy (it was the case of the original Cam clay model) or by proposing directly an educated mathematical expression for the yield locus (modified Cam clay and many other constitutive models). This second alternative is followed here because it leads to a simpler result that concentrates on collapse behaviour.

Consider the model illustrated in Figure 3. The soil response to three loading paths at constant suction (Figure 3a) is given in Figure 3b. Increasing the suction ($s_2 > s_1 > 0$) leads to an increase in yield stress ($Y_0 > Y_1 > Y_2$). Figure 3c shows the yielding points (Y_0, Y_1, Y_2) represented in an (s, p) plane. They define the LC yielding curve. Figure 4 shows the reason for this notation. Consider a point 1 at the yield curve LC_1 for a suction s and a confining stress p_1 . An increase of p from 1 to 2 at constant suction $\bar{s}$ displaces LC_1 towards LC_2 . This path deforms the soil along the virgin compression line for suction $\bar{s}$ (coefficient of compressibility $\lambda(\bar{s})$, Figure 4b). Alternatively, a wetting path from 1 to 3 at constant stress p_1 drags the yield curve to the same new position. In both cases the compression change in void ratio is the same. Therefore, the yield curve LC explains the plastic collapse induced by loading and wetting paths or any combination of increasing stress and suction reduction.

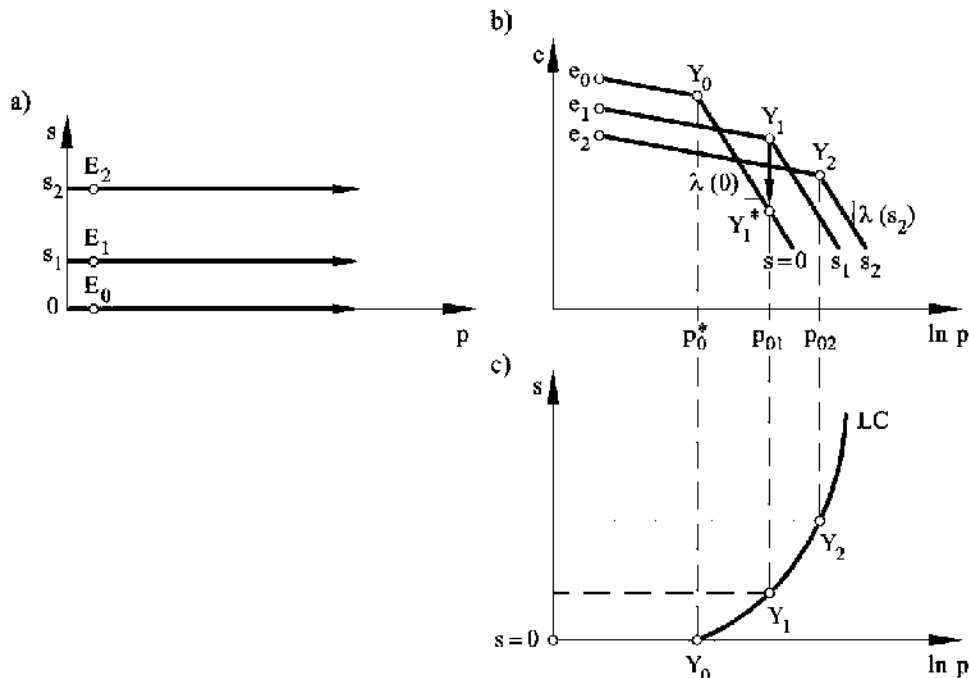


Figure 3. a) Mean net stress loading paths at constant suction; b) Compression curves; c) Loading-Collapse yield curve

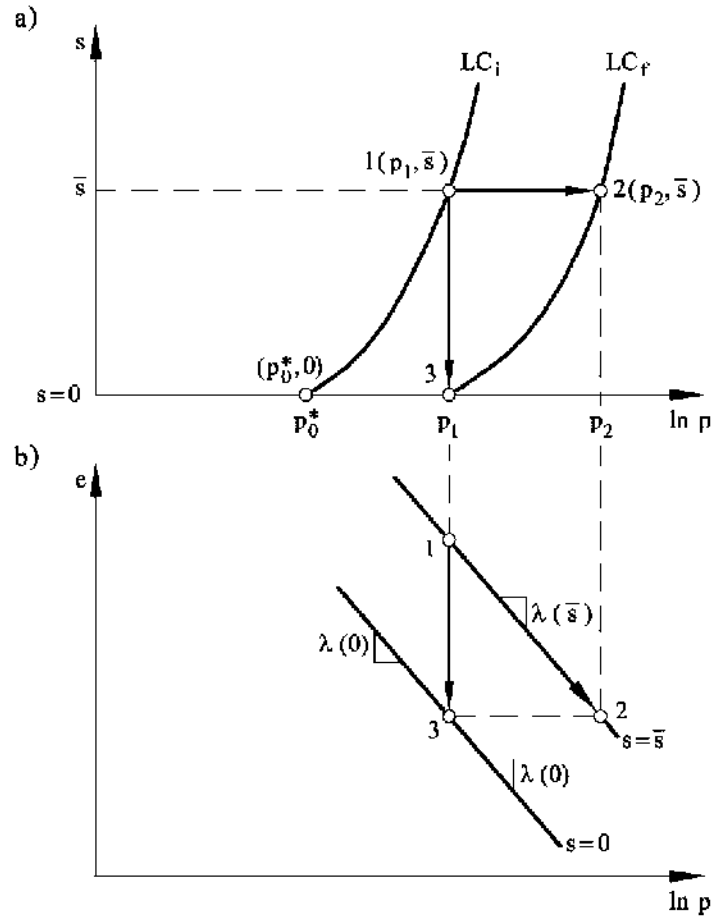


Figure 4. a) Loading and wetting paths; b) Compression curves for constant suction and saturated conditions and expected soil deformations for paths 1-2 and 1-3

The shape of LC is properly defined by test results. Experiments show that yield stress seems to reach an asymptotic behaviour for increasing suction. The following two-parameters (a, α) exponential equation for yielding states:

$$p_0(s) = p_0^* [1 + a(1 - \exp(-\alpha s))] \quad (6)$$

satisfies the asymptotic behaviour ($p_0(s = \infty) = p_0^*[1 + a]$).

Equation (6) only requires three parameters (p_0^*, a, α), against the six parameters of the BBM (Alonso et al, 1990). This simplification has a price: elastic behaviour against p and s changes is disregarded. But the purpose here is to determine loading and collapse plastic strains.

The position of the LC locus in a (p, s) plane is conveniently given by the preconsolidation stress for saturated condition (p_0^*). A logarithmic hardening rule is proposed for this simple LC model in terms of the plastic volumetric strains (as proposed in BBM):

$$d\varepsilon_{vol}^p = \frac{\lambda(0)}{1+e} \frac{dp_0^*}{p_0^*} \quad (7)$$

The implicit assumption of the model is that in loading and wetting paths, the stress state (p, s) remains always at the LC yield curve. In addition, elastic strains are neglected. This is a reasonable hypothesis in a case of wetting paths of a low plasticity sandy clay insufficiently compacted (no swelling strains are expected; see soil description in Section 6).

The plastic volumetric strain increment for any loading and wetting path, from a plastic state in a yield LC is:

$$d\varepsilon_{vol}^p = \frac{\partial \varepsilon_{vol}^p}{\partial p} dp + \frac{\partial \varepsilon_{vol}^p}{\partial s} ds \quad (8)$$

And, in view of Eq. (6),

$$\frac{\partial \varepsilon_{vol}^p}{\partial p} = \frac{\lambda(0)}{1+e} \frac{1}{p_0^*} \frac{\partial p_0^*}{\partial p} = \frac{\lambda(0)}{1+e} \frac{1}{p} \quad (9)$$

$$\frac{\partial \varepsilon_{vol}^p}{\partial s} = \frac{\lambda(0)}{1+e} \frac{1}{p_0^*} \frac{\partial p_0^*}{\partial s} = -\frac{\lambda(0)}{1+e} \frac{\alpha \exp(-\alpha s)}{[1+\alpha(1-\exp(-\alpha s))]} \quad (10)$$

These expressions allow the calculation of the rate of volume change (second term) in Eq. (8). Note that p is directly expressed in terms of the weight of the soil column above a given point.

4 Additional constitutive relations

The first term of Eq. (5) is related to the water retention characteristics of the soil. A common choice is a Van Genuchten (1988) expression in terms of two parameters: s_A (related to the air entry value) and β , that describes the shape of the degree of saturation above the air entry value:

$$S_r = S_{rmax} + S_{rmax}(S_{rmax} - S_{rmin}) \left[1 + \left(\frac{s}{s_A} \right)^{1-\beta} \right]^{-\beta} \quad (11)$$

This equation is defined between two saturation limits (S_{rmax} and S_{rmin}). Expression (11) is needed to calculate the first term in Eq. (5)

$$n \frac{\partial S_r}{\partial t} = n \frac{\partial S_r}{\partial s} \frac{\partial s}{\partial t} \quad (12)$$

that may be expressed in terms of suction through Eq. (11).

The third term in the water balance Eq. (5) refers to the water flow (Darcy). For a vertical flow, Darcy's law in an unsaturated material is expressed in terms of suction head, and elevation head (z).

$$\mathbf{q} = \frac{k}{\gamma_w} \frac{\partial s}{\partial z} - k \frac{\partial z}{\partial z} = \frac{k}{\gamma_w} \frac{\partial s}{\partial z} - k \quad (13)$$

and

$$\text{div}(\mathbf{q}) = \frac{\partial q_z}{\partial z} = \left(\frac{1}{\gamma_w} \frac{\partial s}{\partial z} - 1 \right) \frac{\partial k}{\partial z} + \frac{k}{\gamma_w} \frac{\partial^2 s}{\partial z^2} \quad (14)$$

A power law relates the unsaturated permeability with the saturated permeability and the degree of saturation:

$$k = k_{sat} k_{rel} = k_{sat} (S_r)^m \text{ where } m \text{ is a number, often selected as } m = 3. \quad (15)$$

5 Governing equation of the coupled flow-deformation problem

Collecting the previous results, the balance equation for fluid flow becomes a second order parabolic differential equation for the space distribution and evolution in time of suction along the calculation soil column:

$$\left(n \frac{\partial S_r}{\partial s} - S_r \frac{\partial \varepsilon_{vol}}{\partial p} \right) \frac{\partial s}{\partial t} - S_r \frac{\partial \varepsilon_{vol}}{\partial p} \frac{\partial p}{\partial t} + \frac{k}{\gamma_w} \frac{\partial^2 s}{\partial z^2} + \left(\frac{1}{\gamma_w} \frac{\partial s}{\partial z} - 1 \right) \frac{\partial k}{\partial s} \frac{\partial S_r}{\partial s} \frac{\partial s}{\partial z} = 0 \quad (16)$$

The term $\frac{\partial p}{\partial t}$ requires an additional elaboration. The natural specific weight of the embankment soil can be calculated as follows:

$$\gamma_{nat} = (1 - n)\gamma_s + nS_r\gamma_w \quad (17)$$

Let us assume oedometric conditions for the central soil column in Figure 2. Then, the mean stress at a depth z below the surface of the embankment becomes ($p = (\sigma_v + 2\sigma_h)/3$).

$$p = \int_0^z \frac{1}{3} (1 + 2K_0) [(1 - n)\gamma_s + nS_r\gamma_w] z \, dz \quad (18)$$

And therefore,

$$\frac{\partial p}{\partial t} = \frac{1}{3} (1 + 2K_0) \gamma_w \int_0^z n \frac{\partial S_r}{\partial t} z \, dz \quad (19)$$

The nonlinear character of Eq. (16) prevents, in general, to find an analytical solution for $s(z, t)$. But it may be integrated by a finite difference approximation. It was solved by a forward Euler method for time derivatives and a central difference approximation for spatial derivatives. The term $\frac{\partial p}{\partial t}$ was approximated by a backward scheme. Some results are given in the next section for the development in time of the initial embankment collapse. The question of the remaining potential collapse in case of additional (heavy) rains will also be answered.

6 Application to a field case

6.1 Geotechnical information of the compacted embankment

The natural soil in the vicinity of the road, selected to build the embankment, was a residual soil from granite. It classifies as low plasticity sandy clay ($w_L=31\%-46\%$; $PI:7\%-25\%$). Figure 5 shows compaction data in a Proctor Plane. Standard Proctor was the reference for embankment compaction. Most of the measured water content lie on the dry side of the optimum. Very often, S_r values are lower than 0.6. This is an indication of a substantial collapse potential. Average in situ porosity was around 0.35. The heavy rain period led to the embankment collapse. Samples were tested to check the collapse potential left in the embankment after the wetting episode. The degree of saturation was measured in a few samples taken at varying depths below the axis and shoulders of the embankment platform. Figure 6 shows the results. In a majority of cases S_r had increased from compaction conditions ($S_r \approx 0.6$) to S_r values around $S_r = 0.8$.

Oedometer tests were performed to determine collapse strains, at full saturation, under vertical stresses reproducing the in situ vertical total stress. Figure 7 shows one result for a sample recovered at a depth of 3.5 m (equivalent to a vertical stress of 0.07 MPa for a unit weight of 20 kN/m³). The sample was loaded (0-0.07 MPa), saturated (a collapse of 4% is measured), loaded further to a vertical stress of 0.8 MPa and unloaded. The test shows a virgin saturated compression coefficient of $C_c = 0.054$ ($\lambda = C_c/\ln 10 = 0.024$). Note that the collapse model developed has a constant compressibility parameter, $\lambda(0)$, irrespective of suction. Similar tests, in samples from different depths, exhibited (remaining) collapse strains at full saturation in the range of 0.5-2%.

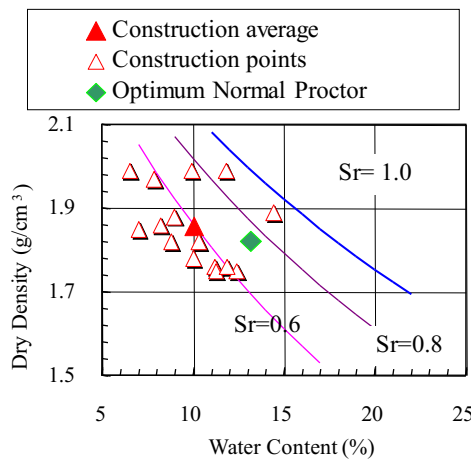


Figure 5. Compaction data

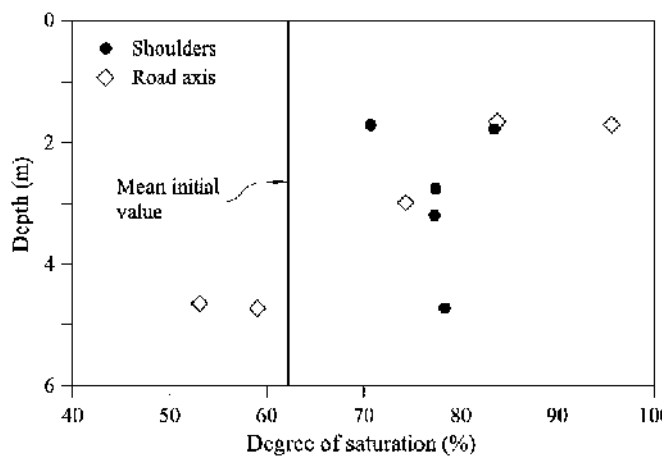


Figure 6. Degree of saturation in the embankment after the rain

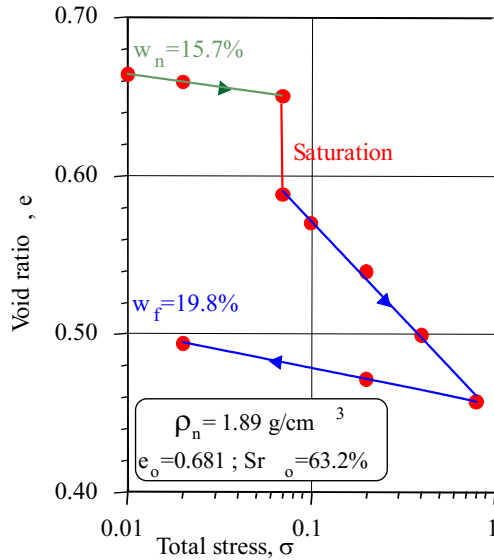


Figure 7. Oedometer collapse test of a sample from the embankment taken at a depth of 3.5 m

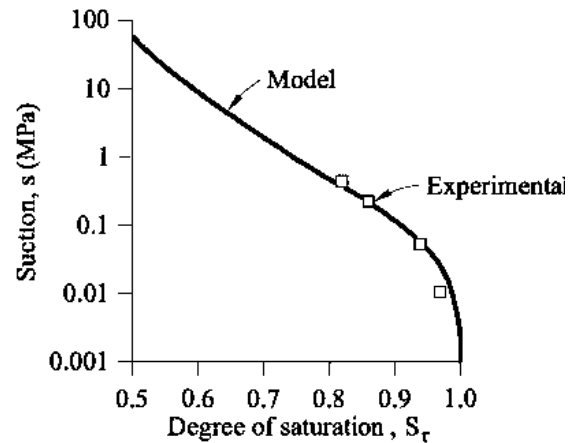


Figure 8. Water retention curve, for a wetting path, of a recovered sample from the embankment

A water retention curve was measured, in a wetting path, in a sample having an initial suction of 0.4 MPa. This suction was reduced in steps, in an oedometer cell under the estimated in situ vertical stress. Figure 8 shows the results. A Van Genuchten model with parameters $S_{rmax} = 1$; $S_{rmin} = 0.5$; $\beta = 0.09$; $s_A = 0.5$ MPa fits well the experiments. Note that the estimated average field initial suction for $S_r = 0.6$ is $s = 8$ MPa.

6.2 Modelling embankment settlement

The preceding description of compacted soil properties is not complete. The parameters a and α of the LC yield locus were not determined by means of laboratory tests. However, the measured embankment settlement under a prolonged and heavy rainfall for an 8 m high embankment provides a useful information that may be used to derive the constitutive parameters by an inference procedure. Figure 9 shows three LC yield curves for increasing confining stress. Point A corresponds to a P value expected at a depth of 5 m (for $\gamma_{nat} = 20$ kN/m³ and $K_0 = 0.5$) and a suction of 8 MPa estimated previously for $S_r = 0.6$. Two additional LC curves correspond to depths of 2 m and 7 m. The figure is plotted for an estimation of LC parameters: $a = 20$ and $\alpha = 0.5$ MPa⁻¹. This is all that was needed to calculate volumetric strains due to an increase in soil weight (due to the increase in water content) and a reduction in suction that dominates the collapse deformation.

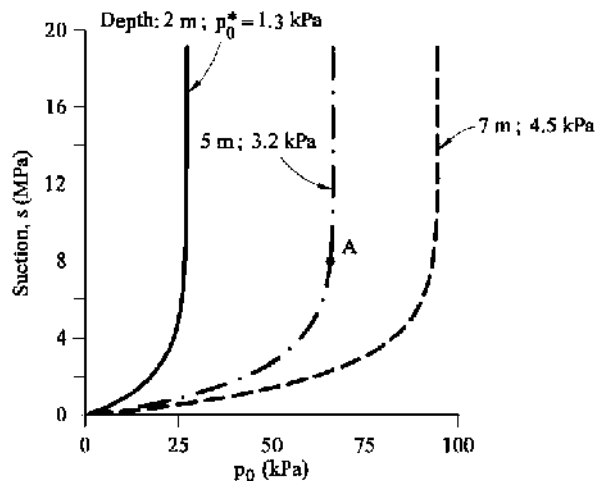


Figure 9. LC curves for different hardening parameters

In fact, these deformations, (loading path 1-2 and wetting path 1-3 in Figure 6) can easily found:

Path 1-2: Integrating Equation (8) at constant suction:

$$\Delta \varepsilon_{vol}^p = \int_{p_1}^{p_2} \frac{\partial \varepsilon_{vol}^p}{\partial p} dp = \int_1^2 \frac{\lambda(0)}{1+e} \frac{dp_0^*}{p_0^*} = \frac{\lambda(0)}{1+e} \ln \left(\frac{p_{02}^*}{p_{01}^*} \right) = \frac{\lambda(0)}{1+e} \ln \left(\frac{p_2}{p_1} \right) \quad (20)$$

Path 1-3: Integrating Equation (8) at constant stress:

$$\Delta \varepsilon_{vol}^p = \int_{s_1}^{s_3} \frac{\partial \varepsilon_{vol}^p}{\partial s} ds = \int_{s_1}^{s_3} \frac{\lambda(0)}{1+e} \frac{1}{p_0^*} \frac{\partial p_0^*}{\partial s} ds = -\frac{\lambda(0)}{1+e} \int_{s_1}^{s_3} \frac{a \exp(-as)}{[1+a(1-\exp(-as))]} ds = -\frac{\lambda(0)}{1+e} \ln \left[\frac{1+a-a\exp(-\beta s_1)}{1+a-a\exp(-\beta s_3)} \right] \quad (21)$$

These expressions allow the calculation of embankment settlements in a one-dimensional column discretised in length elements and the calculation time discretised in time increments.

The solution of the parabolic differential equation, Eq. (16), by finite differences, provides the evolution in time, t , and position, z of suction s and, independently, the total stresses, p (because of changes in soil specific weight).

6.2.1 First wetting

The boundary conditions for the rainfall induced wetting of the embankment column were simulated by setting the suction to 0 on the upper and lower surfaces. The condition at the lower elevation of the embankment was suggested by the observed position of a shallow water table.

Starting at a uniform suction of 8 MPa, Figure 10 shows the calculated suction isochrones. After one day, the value of suction of the entire soil column is close to a small fraction of 1MPa. This is the result for a relatively low saturated permeability of the soil ($K = 10^{-7}$ m/s). However, the suction gradients for the rather dry initial state of the soil were very high. Figure 11 shows the calculated evolution of crest settlement of the embankment for a time period of 3 days. The calculated top settlements (30-40 cm) for an 8 m high embankment were close to field observations.

6.2.2 Additional collapse settlements

Only in case of an additional reduction of suction below the minimum value of the suction remaining after the initial wetting, there is a risk of further settlement. This is easily explained by the LC plastic model (Figure 5). Therefore, the calculation to answer the question was to maintain the infiltration for time in excess of 3 days. The settlement prediction for an addition time period of 3 days indicates that one to three additional days of water infiltration results in additional settlements of 1-2 cm.

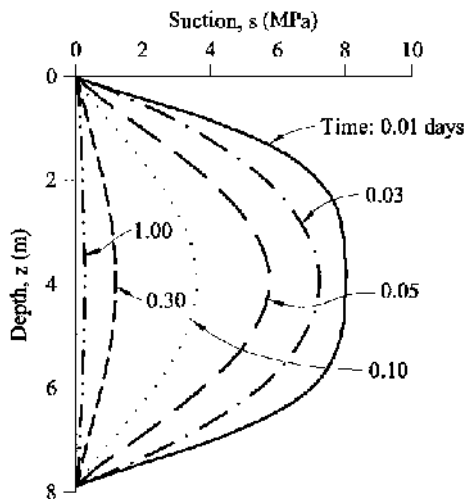


Figure 10. Calculated isochrones of suction

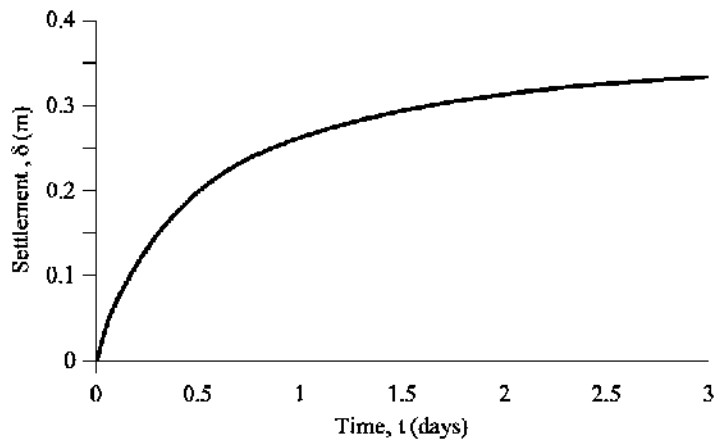


Figure 11. Calculated settlements due to saturation of the two column boundaries

7 Conclusions

The analysis described in this paper and its application to a real case, lies between two extreme approaches. The first one would be a simple “oedometric” type of calculation of the settlement of a column of collapsible soil when it becomes saturated. A few collapse tests at full saturation, for samples recovered at different depths, before the heavy rainfall, would provide collapse strains that could be integrated to yield a total collapse settlement. However, the road authorities were interested in the remaining collapse potential. This question would require some additional information, such as a flow calculation for a rigid soil, to keep it simple, and some procedure to relate suction changes and strains, in other words, an existing “constitutive” model whose parameters need to be identified. This simple approach becomes rapidly unfeasible. The other extreme is to resort to a Finite Element program capable of handling coupled flow-deformation problems for unsaturated soils.

This paper provides an intermediate but powerful approach that isolates the fundamental physical aspects of the problem and achieves a conceptual representation that disregards secondary sophistication. Such an approach may provide correct answers to the questions asked.

In our case the challenge was to build a coupled flow-deformation model for unsaturated soils prone to collapse that is respectful with the key aspects of the problem and could be solved by a limited calculation effort. In addition, the steps described help to follow more complex cases, essentially associated with 2D and 3D spatial formulations. A detailed explanation of how the different “pieces” of the soil behaviour fit into a prediction framework enhances the need to understand theories and available computational procedures. This understanding is a necessary characteristic of engineering education.

The paper also shows how to formulate a simplified but powerful plastic model to describe consistently collapse phenomena. It may be considered as a “mini BBM” model. Its formulation in terms of two independent constitutive stresses (total stress and suction) helps to interpret laboratory tests and to deal with boundary value problems. Suction provides the link between flow and mechanical behaviour.

The analysis performed of a real case has the advantage of relating the formal mathematical formulation with field observation. It also adds some geotechnical lessons: compaction on the dry side leads to a risk of collapse, collapse strains are essentially irreversible (unlike swelling strains) and capillary rise from shallow water should be accounted for in rainfall-induced wetting.

References

- Alonso, E. E., Gens, A., High D. W. (1987). Special problem soils. General report. Proc. 9th European Conf. Soil Mech & Found. Engng, Dublin, 3, 1087- 1146.
- Alonso, E. E., Gens, A., Josa, A. (1990). A constitutive model for partially saturated soils. *Géotechnique* 40(3), 405–430.
- Van Genuchten, M. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am.* 44(5), 892–898.

Authors' bios

Núria M. Pinyol, Universitat Politècnica de Catalunya (Spain)

Núria M. Pinyol is associate professor in the Department of Geotechnical Engineering at Universitat Politècnica de Catalunya (UPC). Her research focuses on thermo-hydro-mechanical couplings in porous media from a theoretical, numerical and experimental point of view. She started as an assistant professor in 2010 after finishing her PhD providing support on Master Courses on Underground Excavation. Nowadays, she is also professor on Soils Mechanics and Geotechnics in both under-degree and master courses. She is co-author of two original books published in Springer entitled “Geomechanics of Failures” and “Geomechanics of Failures. Advanced Topics”. Since 2013, she is responsible of a course based on these two books incorporated in the UPC Master in Civil Engineering

and in the specialized UPC Master on Geotechnical Engineering. She also gives part of this course in other centers in an intensive-course format. She also participated in specialized courses on specific topics (i.e. constitutive modelling, unsaturated soils, numerical modelling, and training courses codes).

Eduardo E. Alonso, Universitat Politècnica de Catalunya (Spain)

Eduardo Alonso is Emeritus Professor at UPC, Barcelona. He was one of the founders of the Civil Engineering School in 1974. He organized and was the teacher of several courses in the field of Geotechnical Engineering at Undergraduate, Master and Doctorate level (Soil Mechanics, Geotechnical Engineering, Rock Mechanics, Underground Excavations, Geomechanics, Probability and Heterogeneity in Soil Engineering). He has taught short courses on Unsaturated Soil and Rockfill Mechanics in Universities and Research Institutions in many countries around the world. He is the co-author of two original books on “Geomechanics of Failures” (Springer) that are the reference textbooks for a post graduate course very much appreciated by Master and Doctorate students at UPC and at ETH (Zürich).

Teaching unsaturated soil mechanics in a South African context

T.S. da Silva Burke & C.J. MacRobert

Stellenbosch University, Stellenbosch, South Africa
taliaburke@sun.ac.za, macrobert@sun.ac.za

ABSTRACT: With South Africa's arid and semi-arid climate, geotechnical engineers frequently work with unsaturated soils. Problem soils such as expansive clays, collapsible soils, and sinkholes are primarily influenced by soil water content changes. Tailings storage facilities (TSFs) also involve complex saturated/unsaturated conditions. However, despite its relevance, unsaturated soil mechanics (USM) is often overlooked in geotechnical engineering practice and education in South Africa. A survey of academics and practitioners examined the adoption of unsaturated soil mechanics in industry and education. Academics highlighted the limited time available and the need to balance the teaching of civil engineers and specialist geotechnical engineers. Limited application in industry was noted by practitioners, with key challenges including appropriate laboratory characterisations of unsaturated soils and hesitation in relying on suction. Simple case studies in seepage and stability showed that USM increases seepage by up to 10%, with nominal increases in stability reported. Changes in steady-state seepage and strength gain considerations from suction effects have limited impact relative to modelling uncertainties. While best suited for postgraduate study, a conceptual understanding of unsaturated soil behaviour should be integrated into undergraduate education, especially regarding volume change in problem soils prevalent in South Africa.

Keywords: Unsaturated soils, Problem soils, South Africa

1 Introduction

Great strides have been made to understand unsaturated soil mechanics (USM), also known as partially saturated soils, albeit primarily in the realm of research. The degree to which a soil is saturated is now known to have a significant impact on a soil's permeability, shear strength and volume (Fredlund et al., 2012). The significance of this impact depends on the size of grains making up the soil. In general, as grains get smaller, the larger the suctions that can develop as the degree of saturation decreases. This decreasing saturation will significantly reduce permeability, increase shear strength, and have a variable impact of soil volume depending on the soil type and mineralogy. The extension of this knowledge to teaching of soil mechanics and routine geotechnical engineering practice has been limited (Pantazidou et al. 2024; Fredlund, 2021). Soil mechanics is largely taught and practiced at extremes: soil is either dry or fully saturated (Santamarina, 2015). This no doubt reflects the reality that most theories have been developed and validated at these extremes without seeing them as a subset of unsaturated soils.

Wirth et al. (2017) conducted a review of ten international undergraduate course curricula in the soil mechanics / geotechnical engineering specialisation; only one of the curricula explicitly included flow in unsaturated soils and mechanical behaviour of unsaturated soils. This highlights the challenge of sufficient time and space in the existing geotechnical courses to include unsaturated soils, which may be considered 'advanced' material. The proposed ideal curriculum recommenced that an introduction to USM be included, noting specifically aspects of flow, constitutive stresses and hydromechanical behaviour.

A challenge in the teaching of soil mechanics at an undergraduate level is the appropriate recognition of material that is relevant to students studying civil engineering as a general degree (Wesley, 2015). With limited time available civil engineering students need to develop a general understanding of soil

behaviour as opposed to that of a specialist geotechnical engineer. As noted by Barashov in the appendix of Santamarina (2015), “specialisation requires a second degree”. The focus should thus be on laying an appropriate foundation for both general civil engineers and future geotechnical specialists whilst “not saying anything in an undergraduate course that would have to be taken back in a graduate course” (Seed, 1986; cited in Pantazidou et al. 2024).

The main challenge to the adoption of USM in undergraduate teaching appears to be related to the limited time available in the curriculum. So, what are some of the key concepts that should be taught? Wesley (2015) suggests that students lack an adequate understanding of “pore pressure state above the water table” and an appreciation that seepage can take place above the water table, the effects of which can be significant especially in clays. Atkinson (2008) suggests that students should have an appreciation that negative pore pressures can develop giving soils different strengths depending on grain size. These teaching suggestions seem minor, compared to the range of applications of USM suggested in literature: seepage in embankments, infiltration triggered landslides, compacted materials, evapotranspiration cover systems, expansive soils and interpretation of plate load tests (Siemens, 2018; Houston et al., 2023; Fredlund et al., 2012).

Another hurdle to teaching USM at the undergraduate level is a lack of teaching resources. Pantazidou et al. (2024) note the limited coverage on USM in introductory geotechnical textbooks. Presentation of this material would thus require reference to specialist textbooks (e.g. Fredlund et al., 2012; Lu & Likos, 2004) and/or relevant research papers. Most undergraduate students will need significant scaffolding to appreciate the content in these resources with their limited technical vocabulary. For instance, Pantazidou et al. (2024) point out the difficulties in the understanding of the key state variables required to describe the behaviour of unsaturated soils.

Saturated soil mechanics has developed the Terzaghi effective stress as the key state variable that predicts the soil behaviour. Initial attempts at understanding USM attempted to create a similar, single effective stress value using the measured suction and a factor related to the degree of saturation (Bishop, 1959). Later developments considered net stress and matric suction as two separate state variables as they impact soil behaviour in different ways (Fredlund and Morgenstern, 1977). The two different approaches remain prevalent in USM research, with some tension as to what the more appropriate and correct description of unsaturated soil behaviour is (Pantazidou et al., 2024). As an illustration of the impact of these alternate approaches, below is an example of how they would be used to explain the simple problem of how a sandcastle stands up:

Approach 1 (Single effective stress state variable): Suction provides an additional confining stress on the soil and increases the effective stress by an amount that is proportional to the degree of saturation. The sandcastle stands up because the suction increases the effective stress of the soil.

Approach 2 (Two independent state variables): Suction and net stress create different responses in the soil and should be considered separately. For positive porewater pressures (saturated soils), these effects disappear, and a single effective stress can be used. The sandcastle stands up because the suction increases the shear strength of the soil.

These nuances are likely a step too far for undergraduate students just coming to terms with a multi-phase material let alone geotechnical engineering lecturers who are non-specialists in USM.

This paper attempts to contextualise the teaching of USM to South Africa. The arid/semi-arid climate of South Africa coupled with residual soils and deep water tables makes USM particularly relevant. Furthermore, the extensive involvement of the geotechnical community in the design and operation of tailings storage facilities requires an appreciation for the impact of unsaturated soil on seepage, strength and volume change. To guide the teaching of USM at the undergraduate level the views of influential South African geotechnical academics and practitioners were sought.

Academics highlighted the limited time available and the need to balance the teaching of civil engineers and specialist geotechnical engineers. Within practice, challenges related to a lack of knowledge and training, limited laboratory facilities for unsaturated soil testing, and a strong tendency for conservatism especially with regards to maintenance of suctions and the magnitude of shear strength increase provided by suctions. Key concepts identified were the need to convey the qualitative impact of unsaturated soil behaviour at an undergraduate level, particularly in the context of problem soils and seepage analyses. Some simple case studies that could be used in teaching the impact of USM on seepage and stability are included for consideration.

2 South African context

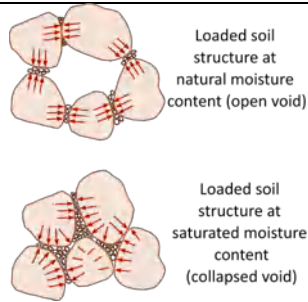
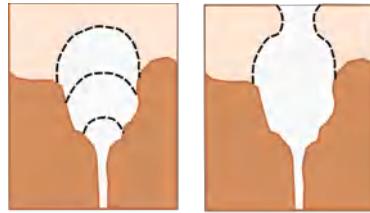
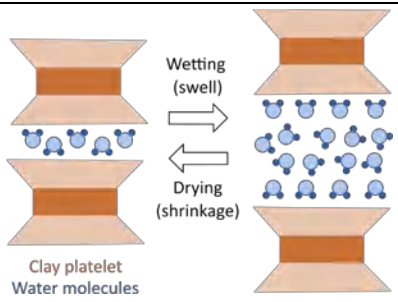
2.1 Climate

Using Thornthwaite's Moisture Index values (Thornthwaite, 1988), approximately 85% of South Africa is classified as having a water deficit where loss by evaporation exceeds supply by precipitation (Paige-Green, 2009). This results in deep water tables in these regions. Water surplus areas occur primarily in KwaZulu Natal and Eastern Mpumalanga along the eastern escarpment of the Drakensburg Mountain range and towards the east coast (Paige-Green, 2009). Much of the country therefore constructs geotechnical infrastructure in unsaturated soil zones.

2.2 Problem soils

In South African geotechnical engineering practice, there are five widely recognised problem soils, namely collapsible soils, dispersive soils, soft clays, dolomites, and expansive soils (Day, 2013). Of these, three are directly related to USM: collapsible soils, dolomites and expansive soils (see Table 1). Their problematic characteristics with respect to volume change are related to the change in moisture content of the soil: if the soil was fully saturated or completely dry, these characteristics would not result in problems in engineering applications in soils of these types. In characterising these soils, it is thus imperative to understand the likelihood of a change in moisture content and the amount thereof to quantify the impact of the problematic behaviour.

Table 1. Problem soils in South Africa with behaviour related to unsaturated soil mechanics

Collapsible soils	Dolomites	Expansive soils
 Loaded soil structure at natural moisture content (open void) Loaded soil structure at saturated moisture content (collapsed void) Image after Houston et al. (1988)	 Progressive collapse of void Collapse of arch to form sinkhole Image after Brink (1979)	 Clay platelet Water molecules Wetting (swell) Drying (shrinkage) Image after Murison et al. (2023)
Leaching of minerals from residual soil profile causes an open grain structure held under load in a pseudo-stable state with contact cementation and suctions. On wetting, the cementation/suction disappears and sudden large changes in volume occur as the voids collapse (Schwartz, 1985).	Stable voids form in soluble rock supported by soil arching in overburden material; unsaturated nature allows tensile strength in soil. Increase in moisture content results in loss of strength and sudden collapse of void (Wagener, 1985).	Clay minerals with negatively charged surface are loosely held by van der Waals forces; on exposure to water, water enters the between the clay particles and drives them apart causing significant increases in volume. The opposite effect occurs as the clay dries out (Williams et al., 1985).

2.3 Tailings Storage Facilities (TSFs)

Tailings refers to the waste by-product from the processing of mineral ores; this is conventionally deposited as a slurry in large embankment dams known as tailings storage facilities (TSFs). Stability of these facilities relies on the sun-drying of these slurries; therefore, their management relies on reducing the water stored as much as possible to promote the development of unsaturated soil conditions (Wates, 2023, Wilson, 2021). The porewater pressure distribution in the unsaturated soil affects the overall seepage, and as shear strength varies with suction, the stability too (Bella, 2021). Material contained within these embankments is prone to static liquefaction as evidenced by notable failures in South Africa including Bafokeng in 1979, Merriespruit in 1994 and Jagersfontein in 2021. Material with a degree of saturation above 85% is considered potentially liquefiable (Wilson, 2021), so understanding where this transition is above the phreatic surface is crucial to assessing overall stability.

3 Ivory towers: Academic voices

To understand the current level of teaching of unsaturated soils in South Africa, academics at tertiary education institutions in Southern Africa (South Africa and Namibia) were asked to give input on whether USM is included in the curriculum and the perceived benefits and challenges of including this topic. The survey included four open-ended questions. Survey questions requested details of USM included in curricula, the value of USM, content that could be added and anticipated challenges. Responses were received from two participants and collated with the authors' own perspectives and experiences at three institutions in South Africa. It was found that USM was not covered in any undergraduate courses and only partially in postgraduate courses. Problem soils were covered in undergraduate courses either within a geotechnical engineering module or in a preceding engineering geology module. At the postgraduate level coverage was limited to guest lectures on unsaturated seepage modelling and a full-day course on USM principles which closely follows the topics presented in Fredlund (2021).

Respondents noted the value of appropriate understanding of USM with one noting *"it will drastically affect the reliability of design, since suction affects strength and volume change in soils"* and another noting the impact of climate change and increased rainfall on slope stability. Academics highlighted the limited time in the curriculum as a challenge to including additional material. Limited instructor knowledge and the time required to prepare related material, as well as limited capacity of the students and the need to ensure that the basics of soil mechanics are well understood before adding complexities were noted as additional challenges. Unfortunately, responses were too generic to identify specific content to teach.

4 Tin huts: Industry voices

To understand how USM is used in South African practice, prominent geotechnical engineers were sent a survey comprising two open-ended questions. The first asked them to give information on which USM principles they used in practice, with a request to provide details why none were used if this was the case. A second question was asked to find out which USM principles they believed should be taught at university (either at undergraduate or postgraduate level). Three responses were received from 30 invited participants.

Principles highlighted included the use of USM in the design of evaporative covers where an understanding of permeability and seepage properties are important; and the *"appreciation of the role that suction plays in keeping slopes up"*. One respondent provided supplementary information on a case study of the matric suction required to ensure adequate stability on existing slopes in the Atlantic Seaboard region in Cape Town, a region that has experienced some significant slope failures during recent heavy rainfall events. Responses highlight that one of the most significant contributions that USM makes in South African practice relates to rainfall-induced instability of unsaturated slopes.

The responses highlighted two primary challenges in the implementation of USM principles; these were (1) reliance on soil suction and (2) access to laboratory testing. In relation to the reliance on suction, one respondent noted that *"practitioners are scared that the conditions can or will change with time or influenced by environment"* and another the *"possibility of soil wetting under flood or ponding conditions i.e. one must assume that the soil will become saturated over the design life of the facility, even in semi-arid climates"*. The fact that *"saturated soil parameters are conservative"* was noted as a corollary to this statement. A related challenge to the reliance on soil suction noted was the difficulty in establishing the in-situ moisture and suction regime, especially using rotary core drilling.

Fundamental to the correct application of USM is the measurement of the soil water retention curve SWRC (alternatively known as the soil water characteristic curve, SWCC). The SWRC relates soil suction to volumetric water content, gravimetric water content, or degree of saturation (Klute, 1965). SWRCs are a basic requirement for USM principles that expresses permeability, strength and volume change as a function of suction (Fredlund, 2021). In international contexts where USM research is more prevalent, the ability to measure the SWRC is readily available and affordable (Fredlund, 2021). However, in the South African context, the situation is different as noted by two respondents *"To my knowledge only UP [University of Pretoria] does SWRC testing; more labs need to do this"* and *"Instruments and methods to measure soil suction, and develop a soil-water characteristic curve, are not offered in commercial laboratories."*

The lack of the laboratory measurement of the SWRC does not preclude the use of USM principles – as noted by a respondent, these can be estimated from “*empirical methods from grading and Atterberg Limits*”. Although not as reliable as direct measurement, these would give sufficient information to understand the change in behaviour from considering saturated/dry material only to including the effects of unsaturated material. This suggests that a related challenge in the application of USM is the lack of awareness and appropriate training for practitioners, although this was not noted by any of the respondents. When considering what aspects of USM should be taught at university, the comments were “*the theory of suction and its contribution to shear strength should be taught*” and “*strength, seepage and volume change with examples of how to test and use in practice*”. Another simply commented that “*all concepts and theories [should be taught] at post graduate level*” without clarifying specifically what the key aspects of these concepts and theories are.

These views largely reinforce factors highlighted by Fredlund (2021) for the slow adoption of USM in routine practice. These factors included complex theories, measurement of suctions in the field, permanency of soil suctions / inability to rely on suctions (disappear after rain) and appropriate laboratory characterisation of soils.

5 Simple case studies

Following are some simple case studies of calculations that can be performed with readily available software (in this case Rocscience’s Slide 2 limit equilibrium software) to illustrate the capabilities of USM and implications compared to assuming that soil is saturated or dry only. At an undergraduate level these case studies would most likely only be for affective purposes, which is to excite and motivate students (Orr & Pantazidou, 2012). At an undergraduate level there is unlikely enough time to fully explain the underlying theory.

5.1 Vadose zone seepage

This case study is used to quantify the effects of the inclusion of unsaturated soil behaviour on total seepage volumes in a simple model of groundwater seepage through a slope. The model comprised a 10 m high, 1:2 slope with a known phreatic surface at a height of 7 m above the toe at the boundary and ponded water with a depth of 1 m at the toe; the model setup is shown in Figure 1 The soil was assigned a saturated permeability, k_s , of 5×10^{-7} m/s, with a vertical to horizontal permeability ratio of 0.5 (more permeable in the horizontal direction).

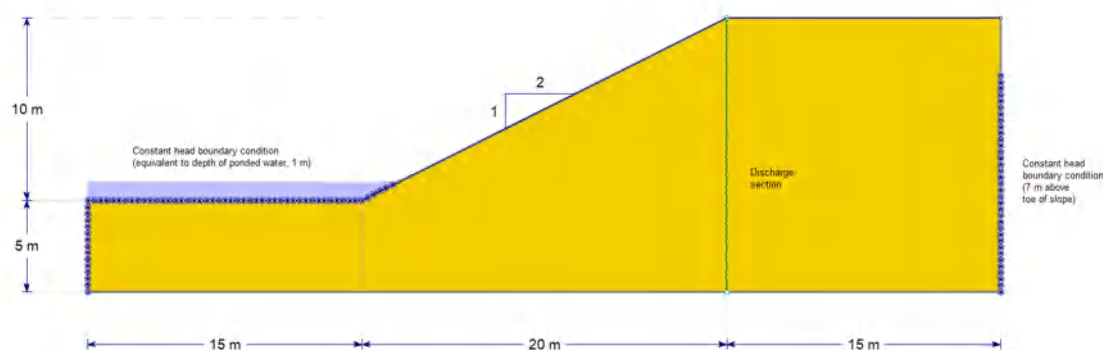


Figure 1. Simple slope limit equilibrium model showing hydraulic boundary conditions

Permeability varies as a function of suction; the particle size significantly impacts the suction that a soil can hold with finer soils able to hold more water and thus sustain greater suctions. This means that more flow can occur in the unsaturated region compared to a coarse-grained soil. The relative permeability, k/k_s , as a function of suction, ψ (measured in kPa), for a sand, silt and tailings are shown in Figure 2 using relationships for example materials from Leong and Rahardjo (1997). The A-value gives an indication of the air entry value (AEV) at which point the air phase becomes continuous and permeability rapidly decreases. To simulate no flow in the unsaturated region, the permeability for negative pore water pressures was set to 1×10^{-13} m/s. The results showed an increase in seepage quantity of 1.9%, 6.1% and 9.6% for the sand, silt and tailings from the case where no flow is assumed in the unsaturated

soil to where unsaturated flow is included. This result is similar to that reported by Siemens (2018) in an analysis of an embankment dam where a 7.6% increase was noted. The phreatic surface was minimally increased with the seepage face exiting a vertical height of 0.5 – 1 m higher on the slope in the case with unsaturated flow. A sample result of the flow vectors for the unsaturated flow in the silt is shown in Figure 3; this highlights the portion of flow that occurs in the unsaturated region primarily below the AEV (8.55 kPa).

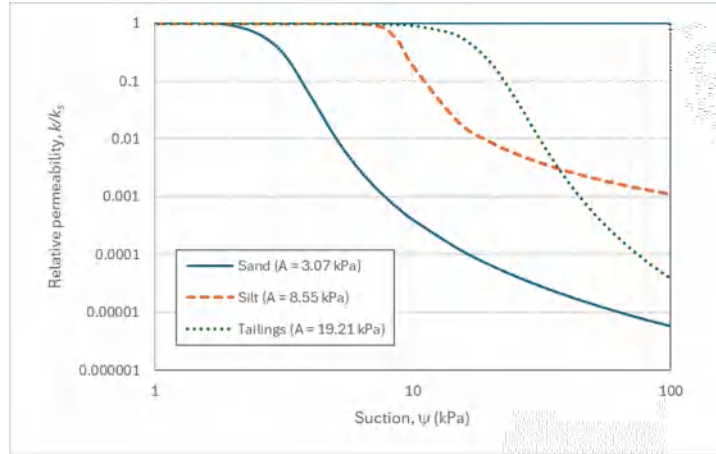


Figure 2. Relative permeability of three sample materials (sand, silt and tailings) showing the significantly reduced permeability once the AEV (indicated by the A-value) is exceeded

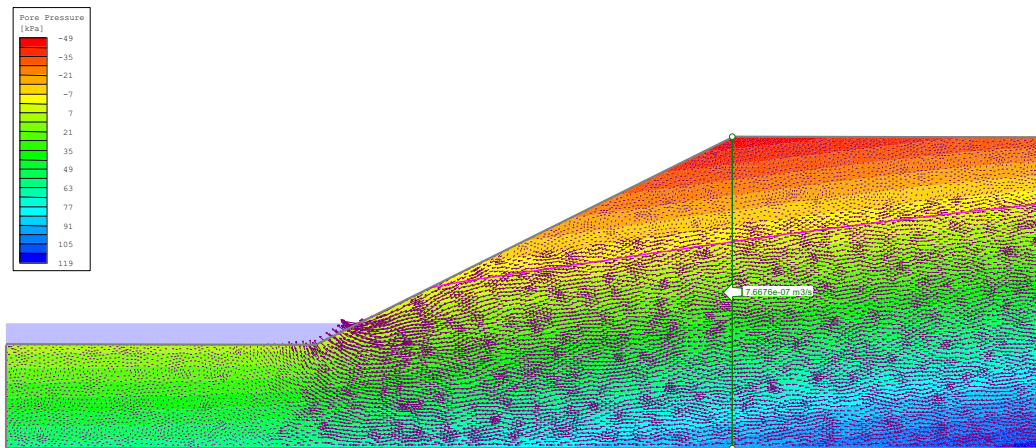


Figure 3. Flow vectors for saturated and unsaturated flow in a silt material

These results could be used to show that it is not correct to assume that no flow occurs above the phreatic surface. Although such an assumption has limited impact on the level of the phreatic surface, it is important to appreciate that flow does occur in unsaturated soils and increases expected seepage in a slope or embankment. For finer-grained soils where the water content remains high as suction increases, the impact of considering flow in the unsaturated region is greater.

5.2 Including suction in a stability analysis

The second case study shows how the factor of safety (FOS) increases because of including strength due to suction in the unsaturated zone. The phreatic surface and pore pressure regime from the seepage model with the silt material ($A = 8.55$ kPa) and the inclusion of flow in the unsaturated soil was used in the stability model. The soil was assigned an internal angle of friction, ϕ , of 35° , and effective cohesion, c' , of 5 kPa. Slide2 assigns unsaturated shear strength, τ , according to Equation 2:

$$\tau = c' + (\sigma_n - u_a) \tan \phi' + \psi \tan \phi^b \quad (2)$$

where $(\sigma_n - u_a)$ is the net stress and ϕ^b is the unsaturated shear strength angle assigned when the suction exceeds the AEV. Two unsaturated strength models were considered, one where $\phi^b = \phi'$,

termed the 'maximum model' as this is the upper limit of the suction-induced shear strength increase, and the second with $\phi^b = 0^\circ$, termed the 'conservative model' due to the limiting value applied to the suction-induced shear strength increase. The shear strength envelopes are shown in Figure 4.

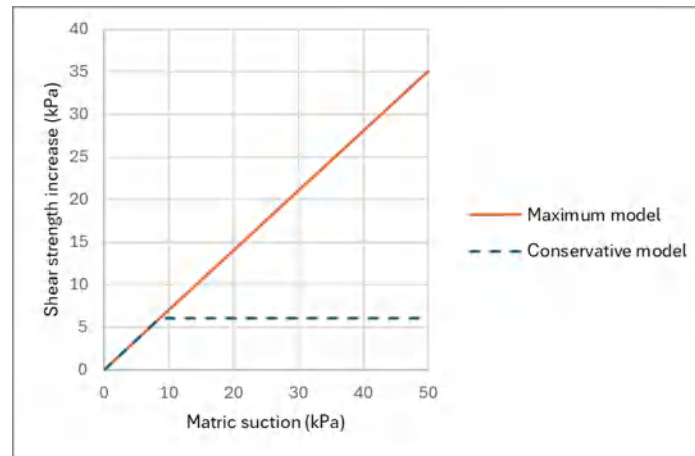


Figure 4. Unsaturated shear strength models used

The FOS results are shown in Table 2 with the corresponding slip surfaces in Figure 5. The simple unsaturated model results in an increase in the FOS by 4.8%; in this model the maximum possible increase in strength in the soil is at the crest of the slope and is 33 kPa (corresponding to 47 kPa of suction), although this is outside of the identified slip circles. The conservative model using a constant shear strength increase after the air entry value gives a slightly lower FOS increase of 4.1% with a maximum shear strength increase of 6 kPa for all regions where the suctions exceed the AEV. These are minor increases in stability which, critically, disappear if only two significant figures are considered which is common in the reporting of slope stability results. However, it is noted that in borderline cases, suctions could contribute to improved stability of slopes as noted by the practitioners in the survey response.

Table 2. FOS safety results

	No unsaturated shear strength	Maximum unsaturated strength ($\phi^b = \phi'$)	Conservative unsaturated strength ($\phi^b = 0^\circ$)
FOS	1.45	1.52	1.51
% increase	-	4.83	4.14

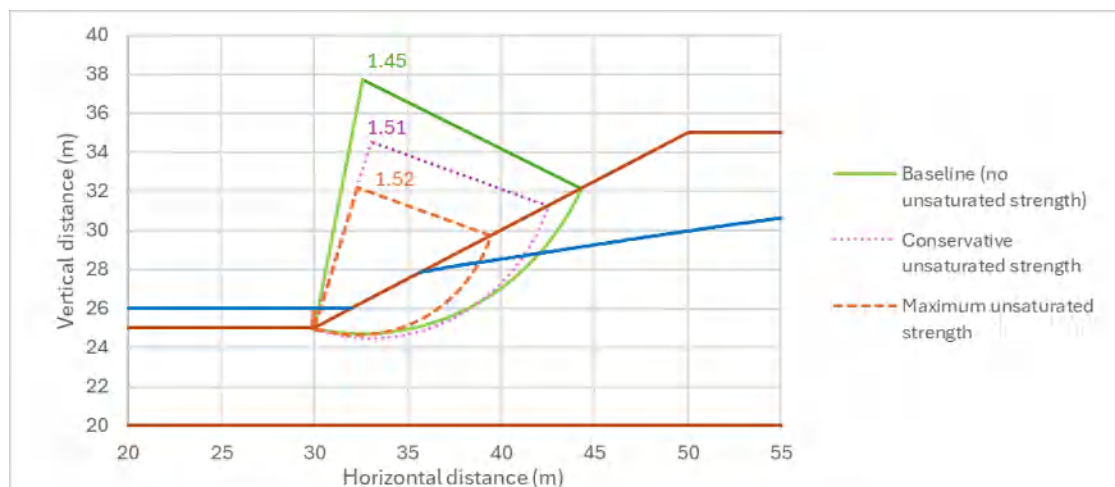


Figure 5. Slip surfaces resulting from saturated and unsaturated shear strength

5.3 Seepage induced instability

The final illustrative example considers the loss of suction due to rainfall infiltration. A transient seepage analysis was conducted with a vertical infiltration flux equal to the saturated permeability applied along the exposed surface of the slope and crest; this is the maximum infiltration that can occur into the soil. For the saturated permeability in the model, this infiltration is equivalent to a constant rainfall of 43.2 mm/day. The porewater pressure profile at the crest of the slope is shown in Figure 6. This shows the relatively slow progression of the wetting front through the slope with only 1 m of infiltration after 20 continuous days of influx (this equates to roughly the mean annual precipitation for South Africa falling in 20 days).

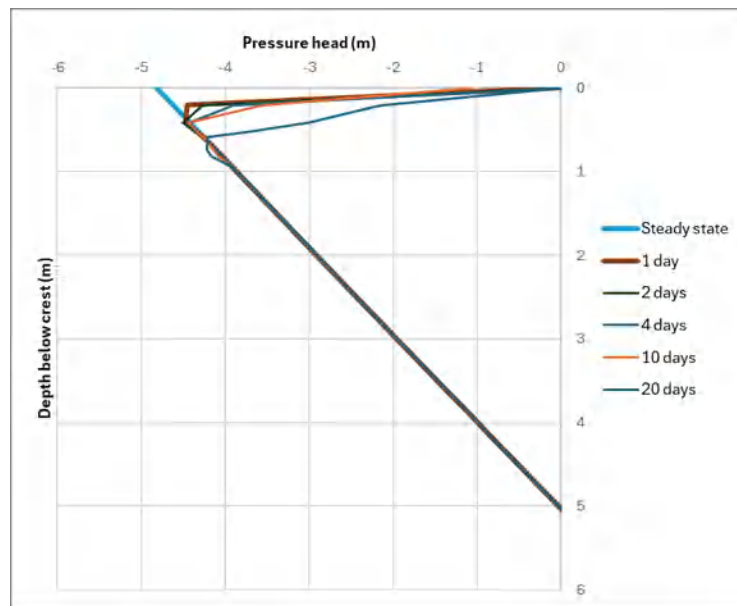


Figure 6. Pressure head profile below the crest of the slope in the transient seepage analysis

The porewater pressure, phreatic surface and stability results are shown in Figure 7 for the initial steady-state condition and after 20 days of infiltration. The results show a limited impact on the phreatic surface and minor reduction in FOS; the maximum strength in the unsaturated zone was used giving an upper bound to the results. This analysis highlights the possibility of relying on suction in the given scenario and provides a tool to allow practitioners to make an informed decision about the implication of relying on suction and the possible range of changes in the pore pressure profile should changes in environmental conditions occur.

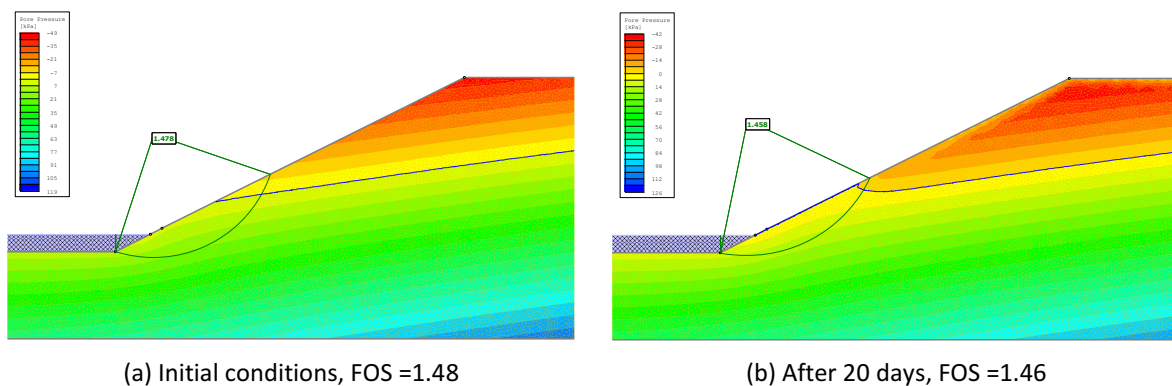


Figure 7. Pressure distribution, phreatic surface and stability results for the transient seepage analysis with infiltration equal to the saturated permeability of the soil

6 Concluding remarks

This paper attempts to contextualise the teaching of USM to South African undergraduates with a focus on local relevance and practice. Due to limited time in the curriculum and the desire to ensure adequate development of core soil mechanics knowledge, detailed presentation of USM principles, including any equations or discussion of relevant state variables, should be left for advanced study. An undergraduate engineer should appreciate that soil is not either dry or saturated, but that a range of conditions exist between these limits. The presence of both air and water in the soil results in suction, which is strongly influenced by particle size. The suction affects the seepage, strength and volume change characteristics of the soil and undergraduates should be able to give a qualitative description of the impacts on soil behaviour; the final observations are structured according to these three areas of influence.

Seepage: all engineers should clearly recognise that flow can occur in unsaturated soils, and that this effect is perhaps counter-intuitively more significant for fine-grained soils. This is because these soils hold onto the water for longer and thus have a higher degree of saturation and consequently higher permeability up to several metres above the water table. This has practical implications in layered soil systems (for instance in waste facilities composed of fine and coarse material) and seepage barriers (gravel layers can be used to break capillary seepage). Characterisation of the seepage influence requires measurement of the SWRC, but this can also be estimated from the grading curve. It is noted however, that unsaturated seepage is likely to have up to 10% effect on steady-state seepage considering saturated flow only. Considering the range of uncertainties in seepage modelling and effect of minor inhomogeneities, modelling results can easily be invalid when compared to reality.

Strength: it is unfortunate that our undergraduate students may graduate without the ability to explain why a sandcastle stands up, one of the first areas of exposure that many have to soil mechanics. Students should appreciate that suction increases the shear strength of the soil and functions similarly to the effective cohesion. This can be used to explain why cut slopes may be more stable in the short-term than in the long-term as the slope dries out. Significant and prolonged rainfall is required to remove suctions, so these can be relied upon where they exist in great degree (e.g. clays). This should be treated with caution however: the examples showed almost insignificant increases in FOS strength for the silt modelled. Suction is only expected to have more marked effects in stability of slopes in fine-grained soils. Variability and uncertainty in estimating primary strength parameters will in most cases have more impact than the suction strength, which is often tacitly accounted for in the nominal effective cohesion values of 2-10 kPa used in coarse materials.

Volume change: USM in the South African context has the largest impact in recognising likely volume change in problem soils. The magnitude of this volume change is not easily demonstrable using readily available software as per the seepage and strength effects, however, qualitative discussions on the USM principles driving the behaviour and where possible physical demonstrations of problem soils should be given. These should show an appreciation of the in-situ moisture content and effect of changes in moisture content on the volume change.

Acknowledgements

This research has been conducted under the appropriate ethical clearance of Stellenbosch University (Ref: REC-2021-23093) The participation of the academics and practitioners in the survey responses is gratefully acknowledged.

References

- Atkinson, J. A. (2008). What should geotechnical engineers be able to do and how should they acquire these skills. Education and Training in Geo-Engineering Sciences, Constantza, Romania.
- Bella, G. (2021). Water retention behaviour of tailings in unsaturated conditions. Geomechanics and Engineering, 26(2), pp. 117-132.
- Bishop, A.W. (1959). The Principle of Effective Stress, lecture delivered in Oslo, Norway, in 1955, published in Teknisk Ukeblad, 106(39), pp. 859-863.
- Brink, A.B.A. (1979). Engineering Geology of South Africa. Silverton, Pretoria: Building Publications.

- Day, P.W. (2013). A contribution to the advancement of geotechnical engineering in South Africa. PhD Thesis, Stellenbosch University, Stellenbosch, South Africa
- Fredlund, D. G. (2021). Myths and misconceptions related to unsaturated soil mechanics. *Soils and Rocks*, 44, e2021062521.
- Fredlund, D. G., Morgenstern, N. R. (1977). Stress state variables for unsaturated soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 103(5), pp. 447-466
- Fredlund, D.G., Rahardjo, H., Fredlund, M.D. (2012). *Unsaturated Soil Mechanics in Engineering Practice*. Wiley
- Houston, S.L., Houston, W.L., Spadola, D.J. (1988). Prediction of Field Collapse of Soils Due to Wetting, *ASCE Journal of Geotechnical Engineering*, 114(1), pp. 40-58.
- Houston, S., McCartney, J., Tarantino, A., Pantazidou, M. (2023). Online Supplement to Pantazidou et al. (2024) <https://www.mygeoworld.com/file/139953/teachingunsaturated-soils-paper-supplement>. [Accessed online: 5 February 2025]
- Klute, A. (1965). Laboratory measurement of hydraulic conductivity of unsaturated soil. In C.A. Black, D.D. Evans, J.L. White, L.E. Ensminger & F.E. Clark (Eds.), *Methods of soil analysis* (Monograph, No. 9, Part 1, pp. 253-261). Madison, WI: American Society of Agronomy.
- Leong, E. C., Rahardjo, H. (1997). Permeability functions for unsaturated soils. *Journal of geotechnical and geoenvironmental engineering*, 123(12), pp. 1118-1126.
- Lu, N., Likos, W.J., (2004) *Unsaturated soil mechanics*. Wiley
- Murison, R. A., Jacobsz, S. W., Gaspar, T. A., da Silva Burke, T. S., & Osman, A. S. (2023). Drying and wetting soil-water retention behaviour of a highly expansive clay under varying initial density. In *E3S Web of Conferences* (Vol. 382). EDP Sciences.
- Orr, T. L. L., Pantazidou, M. (2012). Use of case studies in geotechnical courses: Learning outcomes and suitable cases. *Shaking the Foundations of Geo-engineering Education*. B. McCabe, M. Pantazidou and P. Phillips. Galway, Ireland, Taylor & Francis, pp. 105-110.
- Paige-Green, P. (2009). Use of natural resources for sustainable roads. *Sustainable transport and mobility handbook*, Vol 1, pp. 129-134
- Pantazidou, M., Houston, S., McCartney, J., Tarantino, A., Bardanis, M. (2024). Alert soil mechanics instructors of the main unsaturated soil issues: What and how to teach when experts disagree. In *Proceedings of the XVIII ECSMGE 2024 Geotechnical Engineering Challenges to Meet Current and Emerging Needs of Society* (pp. 727-732). CRC Press.
- Santamarina, J. C. (2015). (What) To teach or not to teach—that is the question. *Geotechnical Research*, 2(4), pp. 135-138.
- Schwartz, K. (1985). Problem soils in South Africa: Collapsible soils. *The Civil Engineer in South Africa*, 27(7), pp. 379-393.
- Siemens, G. A. (2018). Thirty-Ninth Canadian Geotechnical Colloquium: Unsaturated soil mechanics — bridging the gap between research and practice. *Canadian Geotechnical Journal*, 55(7), pp. 909-927.
- Thorntwaite, C.W. (1948). An approach toward a rational classification of climate. *Geographical Review*, 38(1), pp. 55-94.
- Wagener, F. V. M. (1985). Problem soils in South Africa – state of the art: Dolomites. *The Civil Engineer in South Africa*, 27 (7), pp. 395-407.
- Wates, J. (2023). Design criteria for upstream raised tailings storage facilities. *Journal of the South African Institution of Civil Engineering*. 65(2), pp. 10–16.
- Wesley, L. (2015). (What) To teach or not to teach – from theory to practice. *Geotechnical Research*, 2(4), pp. 139 – 147.
- Williams, A. A. B., Pidgeon, J. T., Day, P. W. (1985). Problem soils in South Africa: Expansive soils. *The Civil Engineer in South Africa*, 27(7), pp. 367-407.
- Wilson, G.W. (2021) The new expertise required for designing safe tailings storage facilities. *Soils and Rocks*, 44(3), e2021067521
- Wirth, X., Jiang, N. J., Da Silva, T., Vecchia, G. D., Evans, J., Romero, E., Bhatia, S. K. (2017). Undergraduate geotechnical engineering education of the 21st century. *Journal of Professional Issues in Engineering Education and Practice*, 143(3), 02516002.

Authors' bios

Talia S. da Silva Burke, Stellenbosch University (South Africa)

Dr Talia da Silva Burke is a senior lecturer in Geotechnical Engineering the Department of Civil Engineering at Stellenbosch University. She completed her PhD at the University of Cambridge where she conducted centrifuge modelling to investigate how geosynthetic-reinforced soils respond to the formation of underground voids (e.g. sinkholes). Talia's research interests are related to arching in granular soils, sinkhole deformation mechanisms, geosynthetics and fibre-optic monitoring. She is registered as a professional engineer under the Engineering Council of South Africa and is passionate about teaching and training future engineers to serve society.

Charles MacRobert, Stellenbosch University (South Africa)

Charles John MacRobert is an Associate Professor of Geotechnical Engineering in the Department of Civil Engineering at Stellenbosch University. His education saw him spend time at both the University of Cape Town and University of the Witwatersrand. Research focuses include improving geotechnical design thinking by considering case studies, forensic analysis of failures and participant observation. Specialised consulting is provided for characterisation and modelling of geomaterials for global stability and seepage assessments. This emphasis on practice enables him to confidently teach the professional art of engineering.

Teaching unsaturated soil mechanics through rammed earth

C. Vulpe¹ & C.T.S. Beckett²

¹The University of Western Australia, Perth, Australia
cristina.vulpe@uwa.edu.au

²The University of Edinburgh, Edinburgh, United Kingdom
christopher.beckett@ed.ac.uk

ABSTRACT: From a soil mechanics point of view, rammed earth is a highly compacted unsaturated soil which can also be stabilised. The quirk is that the material is used for construction, i.e. the material finds itself in situations unlike those for 'normal' geotechnical structures. However, the material is tangible and easy for undergraduates to imagine. One distinct aspect of rammed earth is that it dries to much lower water contents than would be found, say, at the ground surface, and so it is particularly vulnerable to moisture (i.e., weakening the material and causing failure). This paper presents a short overview of how basic concepts from unsaturated soil mechanics can be introduced into an undergraduate/post-graduate unit through using rammed earth concepts, such as: Soil Water Retention Curves, matric suction and capillarity, and the contribution of suction to strength through an 'extended' Mohr-Coulomb framework.

Keywords: *Unsaturated soil, Suction, Rammed earth, Geotechnical education, Student learning*

1 Introduction

Environmental geotechnics examines how geotechnical infrastructure impacts and interacts with the environment, for example with respect to groundwater seepage, static and cyclic liquefaction, slope stability, and contaminant transport. However, typical environmental geotechnics topics taught at undergraduate and postgraduate levels involve passive or reactive environmental solutions, which revolve around verbs such as "mitigate", "confine", "contain", "reduce", "remediate".

One method to teach unsaturated soil concepts is to consider rammed earth construction. Rammed earth is, with respect to geotechnical engineering, a highly unsaturated, highly compacted loamy soil, which has been used to construct freestanding structures for millennia (Minke, 2006). Rammed earth is not a traditional geotechnical engineering material or structure or environmental geotechnics solution. However, as a tangible material on the 'human' scale, it is something which students can imagine and understand and, circumstances permitting, with which they can experiment. Furthermore, rammed earth offers an active and positive environmental engineering 'solution' given its association with low or zero carbon footprint construction (Meek et al., 2021), its ability to regulate the hygrothermal behaviour of an enclosed space (McGregor et al., 2016), and the ability to recycle the material *ad infinitum*, introducing with that the ideas of the circular economy (Morel et al., 2021). Lastly, the long history of rammed earth means that structures can be found relating to every culture on every continent (Figure 1), transcending any issues of colonialism.

In this paper, we present the structure of the introductory unsaturated soil mechanics concepts taught in the Environmental Geotechnics unit at the School of Engineering, the University of Western Australia. This is a fourth-level optional unit, and students who choose to take it have already been taught the principles of soil mechanics in previous years. As such, they already come equipped with an understanding of stress state, void ratio, excess pore-water pressure, etc. An introduction to unsaturated soil mechanics is taught over a two-week period. The unit is taught in the flipped mode by means of asynchronous online lectures and synchronous practical workshops, which suits the unit's students who

may be working remotely or scheduling studies around work commitments. The workshops are taught using real-life consultancy industry scenarios (i.e., case studies) and the basic concepts of unsaturated soil mechanics are studied through rammed earth applications.

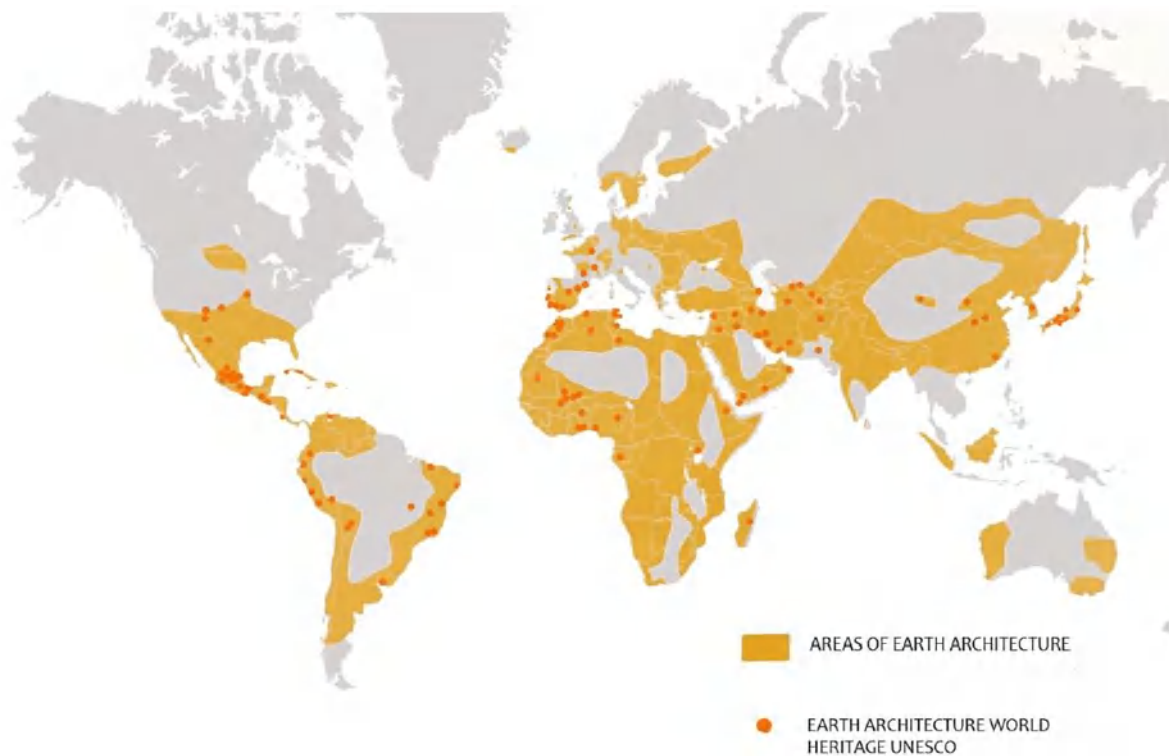


Figure 1. Prevalence of rammed earth structures (Alex, 2018; after Anger and Fontaine, 2009)

2 Teaching using case studies

A definition for 'case studies' is provided by Seshan *et al.* (2021):

"Case study analysis is an active, problem-based, student-centred, teacher-facilitated teaching strategy preferred in undergraduate programs."

It is fitting for how case studies are used in the Environmental Geotechnics unit. Similar to Seshan *et al.* (2021), teaching through case studies in Environmental Geotechnics is meant to stimulate:

- knowledge development;
- critical thinking and problem solving; and,
- communication and collaboration.

The purpose of using case studies in teaching often difficult and/or abstract concepts is to bridge the gap between theory and practice; students get to understand and appreciate how sound theoretical knowledge can be used in solving real world problems such as designing a rammed earth structure. The use of case studies also helps to reduce the gap between a learning environment (the classroom) and engineering practice (e.g., a consultancy firm). This is especially important since the Environmental Geotechnics unit caters to students in the last year of their undergraduate studies.

Through case studies, students are helped to distil difficult theoretical notions (e.g., unsaturated soil mechanics) by immersing themselves into a realistic geotechnical engineering application (e.g., the design of rammed earth wall). There is a secondary, but equally important aspect, in that case studies help students to build confidence in tailoring bespoke engineering solutions to realistic real-life problems. They get accustomed to the idea that there is not a single engineering solution but a multitude of solutions that work in practice as long as they use sound theoretical notions. This means that potentially difficult topics like unsaturated soil mechanics can be successfully taught at undergraduate level in a

short span of time using a number of teaching tools (e.g., flipped classroom, use of case studies, synchronous and asynchronous learning).

3 Unsaturated soil mechanics using the Geotechnical Triangle

Solving real-life geotechnical engineering problems using “empiricism and well-winnowed experience” requires the knowledge of three interlocked aspects (Burland, 1987):

- ground profile;
- soil behaviour; and
- applied mechanics.

Burland (1987, 2008) used these aspects to develop the “Geotechnical Triangle”, shown in Figure 2, which, according to the author, should form the framework for teaching soil mechanics and geotechnical engineering. The Environmental Geotechnics unit leverages the Geotechnical Triangle framework in the design and delivery of its curriculum. This extends to teaching the unsaturated soil mechanics topic, making use both of aspects already included in the original framework (n.b., highlighted in blue in Figure 2) as well as the introduction of new concepts such as the ‘Soil Water Retention Curve’ and ‘suction’ (n.b., highlighted in red in Figure 2).

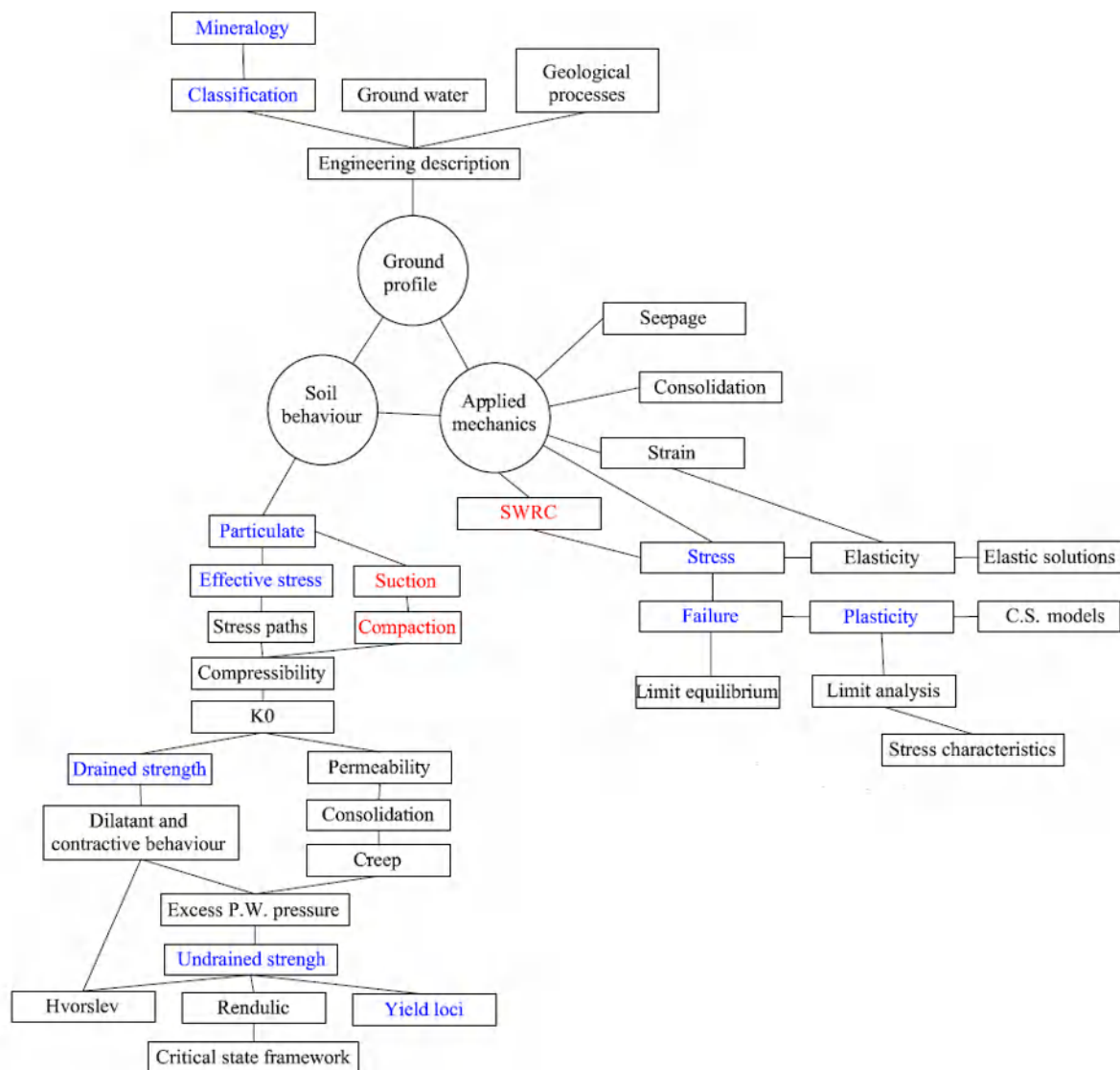


Figure 2. Elements of a basic course in soil mechanics (after Burland 1986) with additions for teaching unsaturated soil mechanics concepts

As mentioned previously, undergraduate engineering students that elect to study Environmental Geotechnics come already equipped with prior knowledge of both basic soil mechanics and advanced geotechnical engineering. Environmental Geotechnics represents at least the third soil mechanics/applied soil mechanics unit that they take. Figure 3 illustrates, in broad terms, that students have already acquired a foundational understanding of the theoretical aspects encompassed by the Geotechnical Triangle and have developed competencies in designing conventional geotechnical engineering applications (for example retaining walls, shallow foundations, and embankments). The Environmental Geotechnics unit builds upon this foundation by offering opportunities to deepen knowledge in advanced geotechnical topics such as cyclic and static liquefaction and unsaturated soil mechanics. This is facilitated through case studies focusing on tailings storage facilities, landfills, and, for the latter, rammed earth structures.

Unsaturated soil mechanics is taught in two distinct parts, presented in greater detail in Figure 3:

- **Ground profile:** This section revisits fundamental soil mechanics concepts, helping students to consolidate their understanding of topics such as mineralogy, particle size distribution, soil classification, and compaction. This foundational knowledge is critical for analysing and interpreting unsaturated soil behaviour and is reintroduced to the students to emphasise how familiar concepts extend to studying the new phenomena.
- **Applied mechanics:** This part introduces advanced concepts, including matric suction, the Soil Water Retention Curve (SWRC), and the influence of suction on soil strength. These ideas are demonstrated using an 'extended' Mohr-Coulomb framework, which integrates the effects of suction into traditional strength theories.

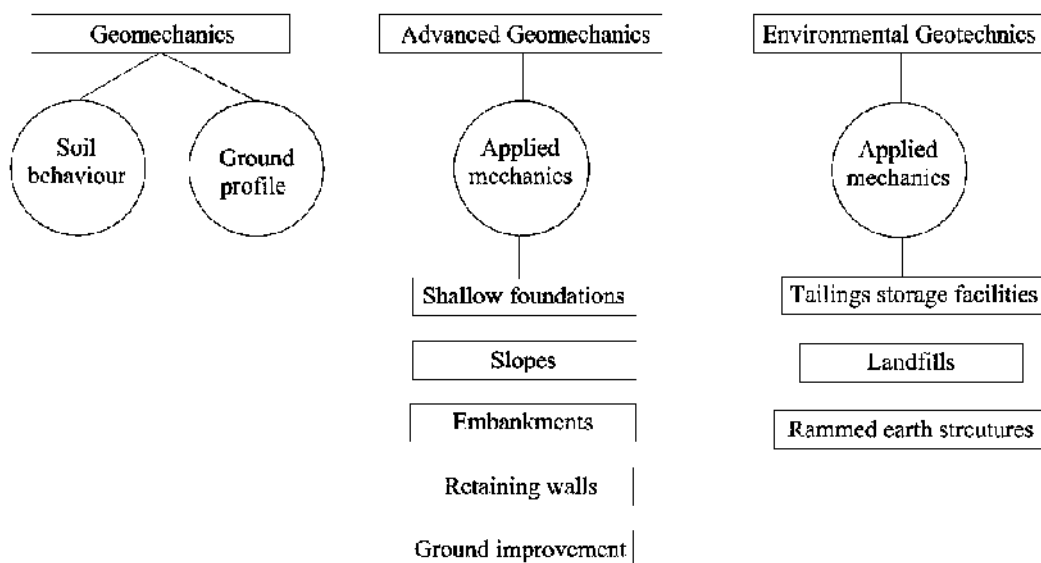


Figure 3. Soil mechanics and geotechnical engineering units at the University of Western Australia

3.1 Ground profile - remembering the basics

3.1.1 Particle size distribution and plasticity

Rammed earth requires a large distribution of soil particle sizes from clay to gravel. Whilst very fine soil is essential in rammed earth, the presence of too much clay, or highly swelling clay, can also lead to structural cracks in the rammed earth walls due to shrinkage.

Particle size distribution by means of wet sieving and characterisation tests (i.e., Atterberg limits) are required in order to establish if a site contains soils suitable for rammed earth. Once the soil particle distribution has been calculated it can be plotted against the allowable particle distribution shown in Figure 4a (Walker et al., 2005). Following sieving, the plasticity of the clayey particles is determined using the Casagrande Cup or Fall Cone apparatus for the liquid limit and the 'rolled threads' for the plastic limit. These test results are then plotted on a plasticity chart (see Figure 4b) to determine if the

soil would undergo linear shrinkage < 5%, namely the plasticity recommended for rammed earth soils (Walker et al., 2005).

The students undertaking Environmental Geotechnics have already studied these basic classification tests in their second year of study through the Geomechanics unit. They have also carried out these laboratory tests in their second year while undertaking the Geomechanics unit. The revisiting of this content in the current unit was deliberate – it offers the students another opportunity to retread what they have studied previously as well as solidifying the concept that basic ground profile investigation is essential in geotechnical engineering practice.

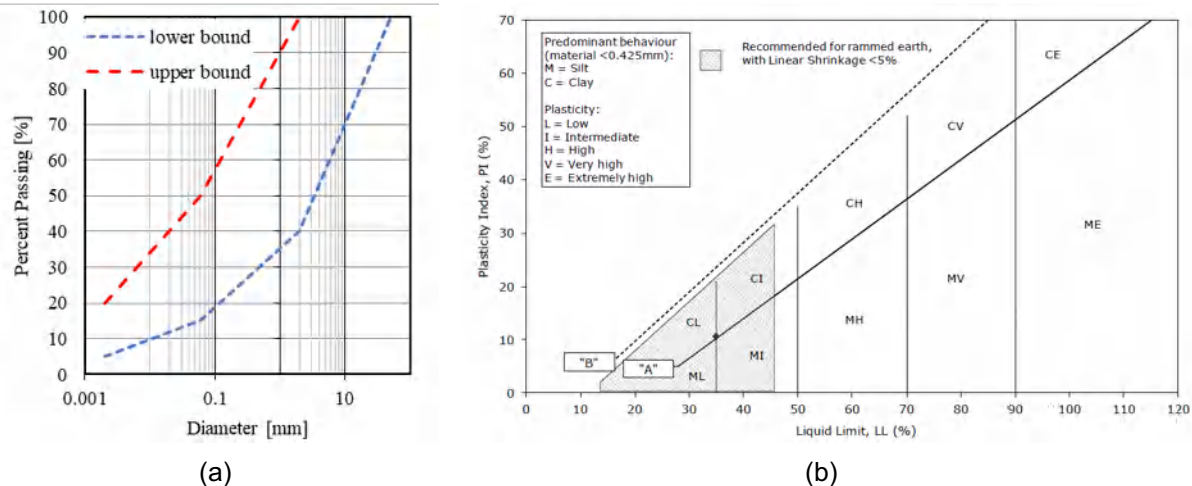


Figure 4. Basic ground profile testing for rammed earth materials: a) particle size distribution plot, b) soil plasticity chart from ASTM Standard D 2487-93

3.1.2 Compaction - Modified Proctor tests

Rammed earth materials are compacted at their optimum water content (OWC) in order to ensure the highest dry density and, by extension, achieve a more stable material with high strength and load-bearing capacity. Laboratory determination of the OWC is generally carried out using:

- the Standard Proctor Test (SPT);
- the Modified Proctor Test (MPT).

The MPT has a compactive effort very similar to that used on-site for rammed earth construction (Beckett et al., 2018) and is a well specified, codified, and widely established test and hence repeatable in any laboratory.

Students have already been introduced to the concepts of soil density (e.g., bulk and dry density) and compaction. The topic of compaction was initially explored within the Environmental Geotechnics unit in the context of compacted clay liners, where the primary objective is to create a continuous hydraulic barrier and to mitigate post-construction settlement. Subsequently, compaction was revisited in the discussion of unsaturated soil mechanics, particularly in relation to rammed earth, where its primary function is to create a sufficiently dense material to be self-supporting and to minimise post-construction shrinkage. The dual examination of compaction from these two perspectives serves to broaden students' understanding of the diverse applications of a fundamental soil behaviour. For rammed earth, the immediate need to achieve a high density (i.e., to create a material of sufficient density to be self-supporting) is obvious.

Revisiting the concept of compaction in different contexts helps students not only to deepen their understanding of soil behaviour but also develops the critical skill of applying foundational principles to solve a variety of real-world problems. Encouraging students to view a single soil behaviour from multiple perspectives fosters creativity and lateral thinking, which are essential for geotechnical engineers.

3.2 Applied mechanics – learning advanced geotechnical engineering notions

In this part, students are introduced to advanced notions in geotechnical engineering, focusing on the behaviour of unsaturated soils. Key topics include:

- Matric suction: understanding the role of pore water pressure and surface tension in influencing soil behaviour.
- Soil Water Retention Curve (SWRC): exploring the relationship between soil suction and water content, a critical tool for characterising unsaturated soils.
- Effect of suction on strength: examining how suction impacts soil strength parameters, demonstrated through the integration of suction effects into an 'extended' and linearised Mohr-Coulomb framework.

These concepts provide students with the tools to analyse and design rammed earth structures, bridging theoretical knowledge with practical application. These topics are presented in lectures and, once complete to the required level, are explored experimentally in the accompanying laboratories.

3.2.1 Matric suction

Matric suction is the component of suction that arises from the curvature of the contractile skin phase. Although osmotic suction will always be non-zero in real soils, owing to dissolved minerals, matric suction can become orders of magnitude greater than the osmotic suction and so is most commonly associated with causing the change in behaviour of a soil between its saturated and unsaturated states (Fredlund and Rahardjo, 1993).

Students taking Environmental Geotechnics have already been introduced to negative pore water pressures through the concept of capillary rise. In most analyses of design cases, however, capillary zones are assumed to be saturated, with the soil taken to be dry above the capillary fringe. Introducing matric suction and its derivation from capillarity encourages students to rethink their understanding of the capillary fringe, for example asking the question of what happens at the air-water interface that must exist in the simplified model of a saturated capillary fringe and the 'dry' soil above.

3.2.2 Soil Water Retention Curve

The degree of saturation in rammed earth is initially around 80-90%, corresponding to the optimum water content at compaction, and drops to below 5% as it dries. This exceptionally low degree of saturation is possible as rammed earth elements are exposed on all sides to the atmosphere, and so dry to a total suction value equivalent to that given by the Kelvin equation for that atmospheric temperature and relative humidity (Beckett et al., 2018). Rammed earth therefore experiences all of the main phases of the SWRC (capillary, funicular, pendular, and adsorbed water). By extending the idea of capillarity into matric suction, as discussed above, students can also understand how the drying and wetting branches of the SWRC are traced out by the emptying or filling of pores of different sizes (and, later, to consider how stress changes induce changes in that pore size distribution and, so, the SWRC). In Environmental Geotechnics, students use the SWRC in three different forms: suction versus the degree of saturation; gravimetric; or volumetric water content, depending on which is the most relevant for the topic at hand, and to become comfortable with selecting appropriate parameters for given tasks.

3.2.3 Suction and strength

Compressive strength is essential to rammed earth. Strength is an intuitive property, indelibly linked to previous soil behaviour topics (Figure 2). Exploring how suction affects soil strength therefore helps to create some continuity across the different taught aspects of Civil Engineering curricula.

As discussed above, Environmental Geotechnics students are familiar with Terzaghi's formulation of effective stress and that a negative pore water pressure will cause an increase in effective stress. In this circumstance, one implicitly assumes that the soil remains saturated or is at a degree of saturation sufficiently high that the change in effective stress equates directly to the change in pore water pressure. However, when the capillary pore water distribution becomes discontinuous, the change in effective stress is no longer directly related to the change in the pore water pressure (Zhou et al., 2016). The simplest method to account for the impact of discontinuous pore water on the effective stress σ' is Bishop's Chi (χ) factor:

$$\sigma' = \sigma - \chi\psi \quad (1)$$

where σ is the total stress, ψ is the matric suction (the negative pore water pressure) and χ takes a value between zero and unity, where it is zero for a degree of saturation $S_r = 0$ and unity for $S_r = 1$. As the degree of saturation also varies between zero and unity, a simplification of Eqn. 1 is:

$$\sigma' = \sigma - S_r \psi \quad (2)$$

i.e. $\chi = S_r$. Fredlund and Rahardjo (1993) showed that Eqn. 2 is valid to extend the Mohr-Coulomb criterion for shear strength in sands. However, Eqn. 2 significantly overestimates the increase in shear strength arising from suction for well-graded soils, for example rammed earth. For sands, the success of Eqn. 2 is predominantly because the air entry value for sands is low (say, 10 kPa) and the degree of saturation rapidly approaches zero thereafter, so that the predicted increase in effective stress is limited. However, the air entry value for rammed earth is higher (approximately 100 kPa) and it can retain water to much greater suctions ($>> 100$ MPa), owing to the small pore sizes of its clay fraction. At these suctions, the water phase exists as menisci trapped in the smallest soil pores and adsorbed to the surface of the soil particles, i.e. not all of the water present is able to affect the solid skeleton, as $\chi = S_r$ implies (Beckett et al., 2018). Studying rammed earth therefore gives students the opportunity to see three stages of the Terzaghi formulation of effective stress:

- the traditional formulation, which is only appropriate for saturated soils (suctions less than the air entry value);
- introducing Bishop's χ (Eqn. 1) and equating it to the degree of saturation (Eqn. 2), which is acceptable for sands but is invalid for soils with pore sizes in the microscopic range;
- modifying the Terzaghi relationship further to account for the discontinuous nature of the capillary water phase at low degrees of saturation, which creates a non-linear relationship between suction, degree of saturation, and strength.

For example, from Beckett et al. (2018), the degree of saturation at a suction of approximately 30 MPa is approximately 10% for rammed earth of a typical particle grading and compacted density (Figure 5a). Taking $u_w = -30$ MPa in Terzaghi's formulation gives an effective stress of 30 MPa (before loading), which is demonstrably unrealistic (e.g. shear strengths may exceed 20 MPa for reasonable friction angles). Using $S_r = 0.1$ in Eqn. 2 gives an effective stress of approximately 3 MPa before considering any loading effects, which gives a considerably smaller but still unrealistic approximation of soil strength if also considering typical friction angles for rammed earth of approximately 40 degrees (Jaquin *et al.*, 2009). Instead, a realistic unconfined compressive strength of rammed earth equilibrated to an atmosphere of modest temperature and humidity will be between 1 and 3 MPa (Beckett et al., 2018 and Figure 5b), i.e. $\chi < S_r$.

3.2.4 Contribution of suction to strength through an 'extended' Mohr-Coulomb framework

Because of the non-linear relationship between degree of saturation, suction, confining stress, and strength, it is useful to dissociate the mechanical and hydraulic contributions to strength via an 'extended' Mohr-Coulomb framework, in which the contributions of suction ($u_a - u_w$) and net stress ($\sigma - u_a$) to the shear strength (τ_f) are considered separately:

$$\tau_f = c' + (\sigma - u_a)\tan(\phi') + (u_a - u_w)\tan(\phi^b) \quad (3)$$

where c' is the effective cohesion, u_a is the pore air pressure (taken as zero), ϕ' is the drained friction angle, and ϕ^b represents the contribution of suction to strength (the term $(u_a - u_w)\tan(\phi^b)$ can be considered an 'unsaturated cohesion').

Fredlund et al. (1987) showed that the surface described by Eqn. 3 is non-linear, i.e. that the values of ϕ' and ϕ^b are not constant, however that, for sands, the surface can be linearised if only considering suction values above the air entry value. Beckett et al. (2018), and, subsequently, others, extended this concept to show that for suctions exceeding the residual value, the failure envelope described by Eqn. 3 also becomes linear (or planar), i.e. ϕ' and ϕ^b are constant (but, notably, ϕ^b is considerably smaller than its value for suctions below the residual value). The linearised failure envelope is shown in Figure 5c and the success of the method to describe changes in compressive strength with suction is shown in Figure 5d. This simplified description makes it easier to introduce the concept of a multi-dimensional failure envelope to students, who must otherwise contend with the ideas that parameters formerly assumed to be constant (ϕ') are not for unsaturated soils. Two example stress states are shown in Figure 5c, where one sample (1, in red) is tested at a higher suction value than a second sample (2, in blue) but achieves a lower shear strength as the net stress for sample (1) is lower. Furthermore, a planar failure envelope lends itself well to experimental verification; rammed earth specimens can be equilibrated to different atmospheric conditions (wherein the total suction is given by the Kelvin equation) and students can measure the change in strength (compressive, for ease) between different equilibration conditions, relating that strength change to the design of structural components and thus combining the

ideas of the extended Mohr-Coulomb framework, the SWRC, the pore size distribution, the Atterberg limits, and the particle grading in one experimental campaign.

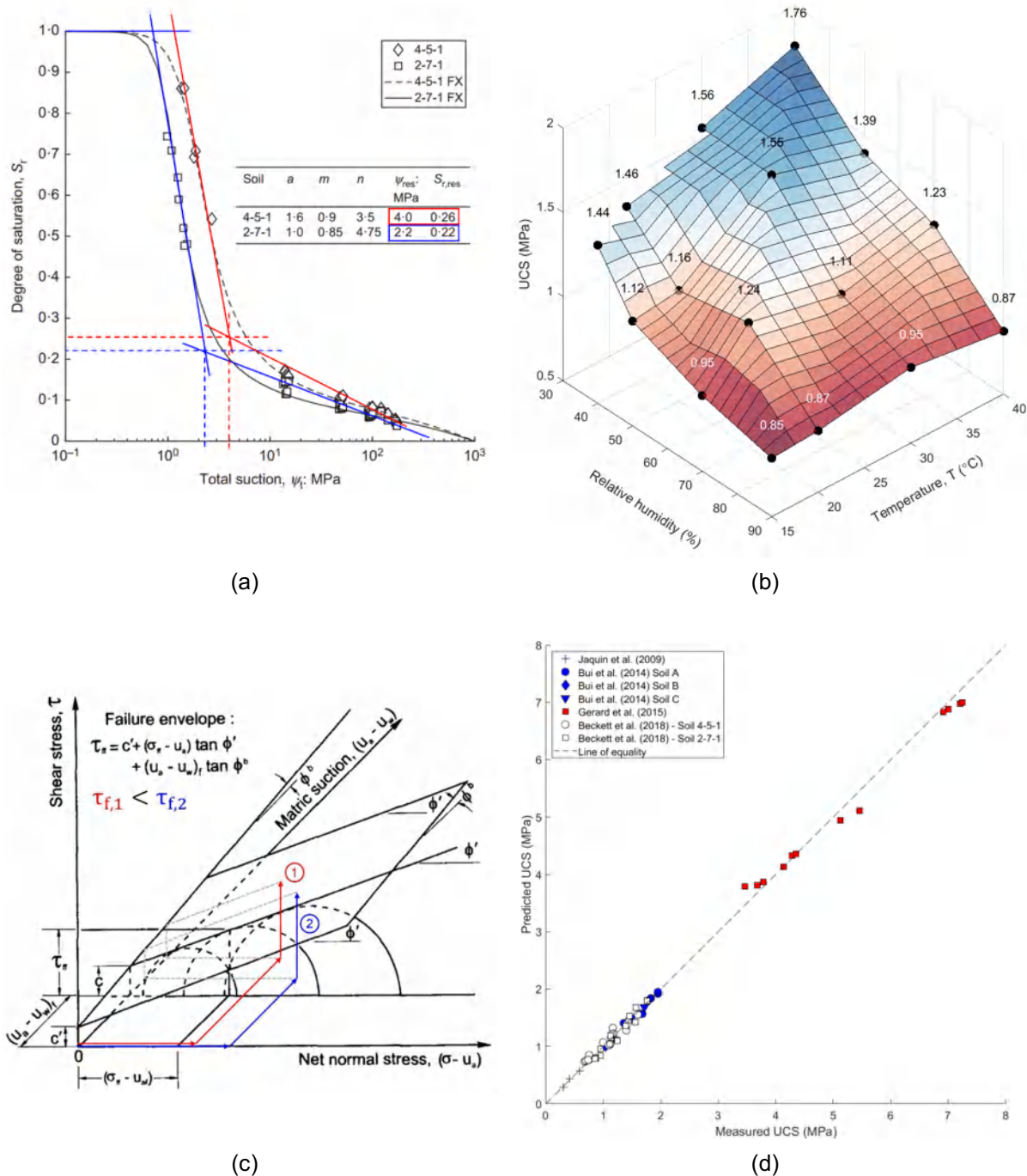


Figure 5. Developing the failure envelope for rammed earth materials: a) identifying the residual suction and degree of saturation ψ_{res} and $S_{r,res}$ (modified from Beckett et al., 2018 where a, m, and n are fitting parameters); b) unconfined compressive strength (UCS) results at different relative humidity and temperature values (redrawn from Beckett et al., 2018); c) linearised 'extended' Mohr-Coulomb failure envelope (modified from Fredlund and Rahardjo, 1993); d) predicted versus measured UCS results for different rammed earth materials under different suction conditions (redrawn from Beckett et al., 2018)

4 Conclusions

This paper has presented how unsaturated soil mechanics is taught in an optional undergraduate unit (Environmental Geotechnics in the School of Engineering at the University of Western Australia) via the platform of rammed earth construction. Rammed earth is essentially a highly compacted unsaturated soil and the technique requires particular soils for construction to achieve the required unconfined compressive strength to support structural loads. It therefore provides an opening to the unfamiliar topic of unsaturated soils from the familiar concepts of (saturated) soil mechanics and structural engineering. The advantages of teaching unsaturated soils from the perspective of rammed earth are threefold:

- i) rammed earth materials span the full range of the degree of saturation, providing an opportunity to discuss the evolution of the soil water retention curve;
- ii) rammed earth failure can be described by a planar failure envelope, which can be interpreted readily by students;
- iii) rammed earth specimens are simple to produce and test in a laboratory, providing students with hands-on experience and personal validation of the effects of suction on unsaturated soil strength.

Overall, the unit is taught in flipped mode and uses case studies in order to stimulate student understanding of difficult abstract topics, and creativity in problem solving. Students revisit basic soil mechanics aspects such as particle size distribution and plasticity, to consolidate the concept that basic ground profile investigation is essential in geotechnical engineering practice, and learn how suction is the key mechanism behind strength and strength gain, modelled according to an 'extended' Mohr-Coulomb failure envelope. By reinforcing the importance of context-specific applications through case studies and linking these to broader geotechnical principles, it is hoped that students develop a more holistic and adaptable approach to problem-solving. This aligns well with geotechnical consultancy industry practice, which also relies on understanding soil behaviour and creative thinking.

References

- Alex, D. (2018). Recognition of a heritage in danger: rammed: earth architecture in Lyon city, France. IOP Conference Series: Earth and Environmental Science, 143, 012054.
- Anger, R., Fontaine, L. (2009). *Bâtir en terre, Du grain de sable à l'architecture* Belin (Cité des sciences et de l'industrie), Paris.
- Beckett, C.T.S., Augarde, C.E., Easton, D., Easton, T. (2018). Strength characterisation of soil-based construction materials, *Géotechnique*, 65, 5, pp. 400-409.
- Burland, J.B. (1987). Nash Lecture: The teaching of soil mechanics - a personal view. Proc 9th European Conf. on Soil Mechanics and Foundation Engineering, Dublin, 3: pp. 1427-1447.
- Burland J.B. (2008). Personal reflections on the teaching of soil mechanics. 1st International Conference on Education and Training in Geo-Engineering Science. Soil Mechanics, Geotechnical Engineering, Engineering Geology and Rock Mechanics, CRC Press and Taylor & Francis Group, London, 35-48.
- Fredlund, D.G., Rahardjo, H., Gan, J.K.M. (1987). Non-linearity of strength envelope for unsaturated soils, Proceedings of the 6th International Conference on Expansive Soils, 49-54, New Delhi, India.
- Fredlund, D., Rahardjo, H. (1993). *Soil mechanics for unsaturated soils*, John Wiley & Sons Inc., New York (USA).
- Jaquin, P.A., Augarde, C.E., Gallipoli, D., Toll, D.G. (2009). The strength of unstabilised rammed earth materials, *Géotechnique*, 59, 5, pp. 487-490.
- McGregor, F., Heath, A., Maskell, D., Fabbri, A., Morel, J.C. (2016). A review on the buffering capacity of earth building materials, *Construction Materials*, 169, pp. 241-251.
- Meek, A.H., Elchalakani, M., Beckett, C.T.S., Grant, T. (2021). Alternative stabilised rammed earth materials incorporating recycled waste and industrial by-products: Life cycle assessment, *Construction and Building Materials*, 267, 120997.
- Minke, G. (2006). *Building with earth - Design and technology of a sustainable architecture*, Birkhauser, Basel.

Morel, J.C., Charef, R., Hamard, E., Fabbri, A., Beckett, C.T.S., Bui, Q.B. (2021). Earth as construction material in the circular economy context: practitioner perspectives on barriers to overcome, *Philosophical Transactions of The Royal Society B Biological Sciences*.

Seshan, V., Matua, G.A., Raghavan, D., Arulappan, J., Al Hashmi, I., Roach, E.J., Sunderraj SE, Prince EJ. (2021). Case Study Analysis as an Effective Teaching Strategy: Perceptions of Undergraduate Nursing Students From a Middle Eastern Country. *SAGE Open Nurs*, 30:7:23779608211059265.

Walker, P., Keable, R., Martin, J., Maniatidis, V. (2005). *Rammed Earth: Design and Construction Guidelines*. IHS Rapidoc (BRE Bookshop).

Zhou, A., Huang, R.-Q., Sheng, D. (2016). Capillary water retention curve and shear strength of unsaturated soils, *Canadian Geotechnical Journal*, 53(6), 974-987.

Authors' bios

Cristina Vulpe, The University of Western Australia (Australia)

Dr Cristina Vulpe is a Senior Lecturer at the University of Western Australia (UWA), working in the broad field of geotechnical asset management. Her work focuses on developing safe and cost-effective solutions for the life cycle management of both onshore and offshore infrastructure. She investigates the whole-life performance of man-made earthen infrastructure and natural landforms by means of advanced geotechnical laboratory testing, numerical simulations, statistical tools, and the integration of emerging smart sensing technologies. This work is undertaken through close collaboration with academic and industry partners. She is also an experienced lecturer, teaching very large (> 350 student) units. She incorporates innovative teaching practices into her classroom (e.g., flipped classroom, use of case studies). Throughout her career, she has consistently attracted a number of Teaching Excellence Award nominations at UWA.

Christopher Beckett, The University of Edinburgh (United Kingdom)

Dr Christopher Beckett is a Senior Lecturer in Geotechnical Engineering and the Deputy Director and Programme Manager for Civil and Environmental Engineering at the University of Edinburgh. He is also an Adjunct Research Fellow at the University of Western Australia. His research focuses on the behaviour of unsaturated soils under extreme states, for example at high temperatures, low degrees of saturation, and when rendered hydrophobic. He teaches advanced geotechnical engineering at the undergraduate level and has been nominated for several teaching excellence awards in his time at Edinburgh. Chris is the Chair of Standard Australia committee BD-083: Australian Earth Building, the Deputy Chair for RILEM TC 319-MAE, Mechanical performance and durability assessment of earthen elements and structures, and the Young Person's Representative for ISSMGE TC-109 Unsaturated Soils.

***Priority Theme 2:
Use of Numerical Modeling to Support Teaching***

Short-term versus long-term stability problems in clay explained through classical figures and finite element simulations

M. Matos Fernandes¹, J.L. Borges¹ & M. Pantazidou²

¹ Faculdade de Engenharia, Universidade do Porto, Porto, Portugal
matos.fernandes@fe.up.pt, leitao@fe.up.pt

² National Technical University of Athens, Athens, Greece
mpanta@central.ntua.gr

ABSTRACT: The construction of embankments on soft clay and the excavation of unsupported cuts in clay are classical reference problems, the discussion of which may be particularly fecund to clear up a number of paramount ideas on the behaviour of fine-grained soils. That discussion may involve issues such as: generation of positive *versus* negative excess pore pressures; undrained *versus* drained soil resistance; short-term *versus* long-term stability conditions; effective stress *versus* total stress analyses; and consolidation as a general phenomenon of dissipation of excess pore pressures whatever their sign. These two problems are the scope of two well-known figures by Bishop & Bjerrum (1960). The paper revisits these figures and provides an expanded interpretation. The usefulness of these figures, and of their detailed discussion, is emphasized and proposed as the closure of a course on Soil Mechanics, as the opening of a course on Soil Engineering, or even both. The discussion on the embankment on soft clay is enriched with results from a finite element simulation that gives emphasis on the change in time of the ground displacements, of the distribution of the excess pore pressures and of the safety factors against a general slip failure.

Keywords: Embankments, Cuts, Clayey masses, Consolidation, Short and long-term stability

1 Introduction

In a basic undergraduate course on Soil Mechanics the most complex issues are typically concentrated in the final part, particularly when the undrained loading of fine soils is discussed and the concept of undrained shear strength is introduced.

It is a real challenge for teachers to explain and for students to understand that, although the undrained shear strength, c_u , is to be used in total stress analyses, its value is totally controlled by the effective stresses, as well as by the excess pore pressures generated by the undrained loading.

An important issue to emphasize is that an undrained loading is always followed by a dissipation of the excess pore pressures, that is, by a consolidation process, which will proceed until equilibrium hydraulic conditions are re-established in the ground mass. And that this phenomenon is critical not only for the time-delayed soil volumetric deformations and for the resulting surface settlements, but also for the stability conditions of the geotechnical structures responsible for triggering the consolidation process.

The discussion of this matter is an excellent field to treat complex topics such as: generation of positive *versus* negative excess pore pressures; undrained *versus* drained soil mass resistance; short-term *versus* long-term stability conditions; effective stress *versus* total stress analyses. This discussion is strongly facilitated if based on two reference geotechnical problems: the construction of embankments on soft clayey soils and the excavation of cut slopes in clays (Lambe & Whitman, 1979; Matos Fernandes, 2020).

This paper is divided in two main parts. In the first part, these two problems are discussed on the basis of two classical figures by Bishop & Bjerrum (1960). In the second part, the problem of the embankment construction is simulated by utilizing a finite element code capable of performing soil consolidation coupled analyses (Borges, 1995). Some numerical results are presented that corroborate the considerations and conclusions of the theoretical discussion based on the first classical figure mentioned above.

2 Classical figures

2.1 Embankment construction on a soft clayey soil mass

Figure 1 contains the classical schematic illustrating the relevant phenomena involved in the construction of an embankment on a soft clayey deposit (Bishop & Bjerrum, 1960).

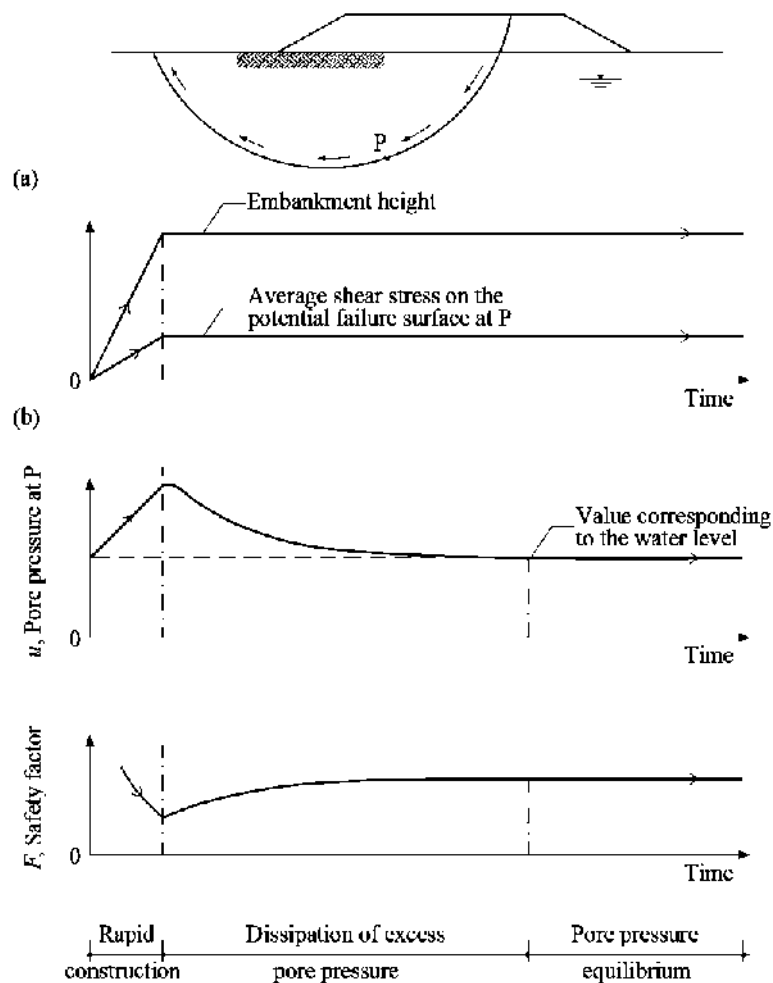


Figure 1. Embankment on soft clayey soil: a) layout and failure mechanism; b) change in time of the shear stress and pore water pressure at a generic point P and of the safety factor (adapted from Bishop & Bjerrum, 1960)

Figure 1 compares changes in quantities during the rapid construction of an embankment on a clay deposit and its post-construction phase, when the consolidation process (dissipation of excess pore water pressure) occurs. These quantities are: a) embankment height (i.e. load) and shear stress along a potential failure surface; b) pore water pressure and factor of safety for a generalized slip failure through the foundation soil and the embankment.

The main idea is that factor of safety varies with time: it increases with time after the completion of the surface loading. Consolidation, i.e., dissipation of excess pore pressure, results in an increase of effective stresses and then of the available soil resistance.

During construction, the load from the embankment is essentially applied under undrained conditions (rapid construction). The increase of the total mean stress and of the shear stress will induce positive excess pore pressure in the depicted soft soil, presumably a normally consolidated (NC) or lightly over-consolidated (OC) clay. This excess pore water pressure reaches a maximum at the end of construction, when the embankment reaches its maximum height.

Then, a two-dimensional (2D) consolidation process is triggered. As water starts gradually flowing out of the loaded soil, the pore pressure decreases, the effective stress increases and so do the shear strength and the factor of safety, which reaches its maximum value in the long-term. Hence, the critical situation for the evaluation of the minimum safety factor for this loading situation (that is, the situation to be considered in the stability analyses) is the end of construction. The conventional procedure to perform these analyses is the limit equilibrium method of slices, assuming undrained conditions and working in total stresses.

2.2 Cut excavation in a clayey soil mass

Figure 2 contains the classical schematic illustrating the relevant phenomena involved in the excavation of a sloped cut in a clay mass (Bishop & Bjerrum, 1960).

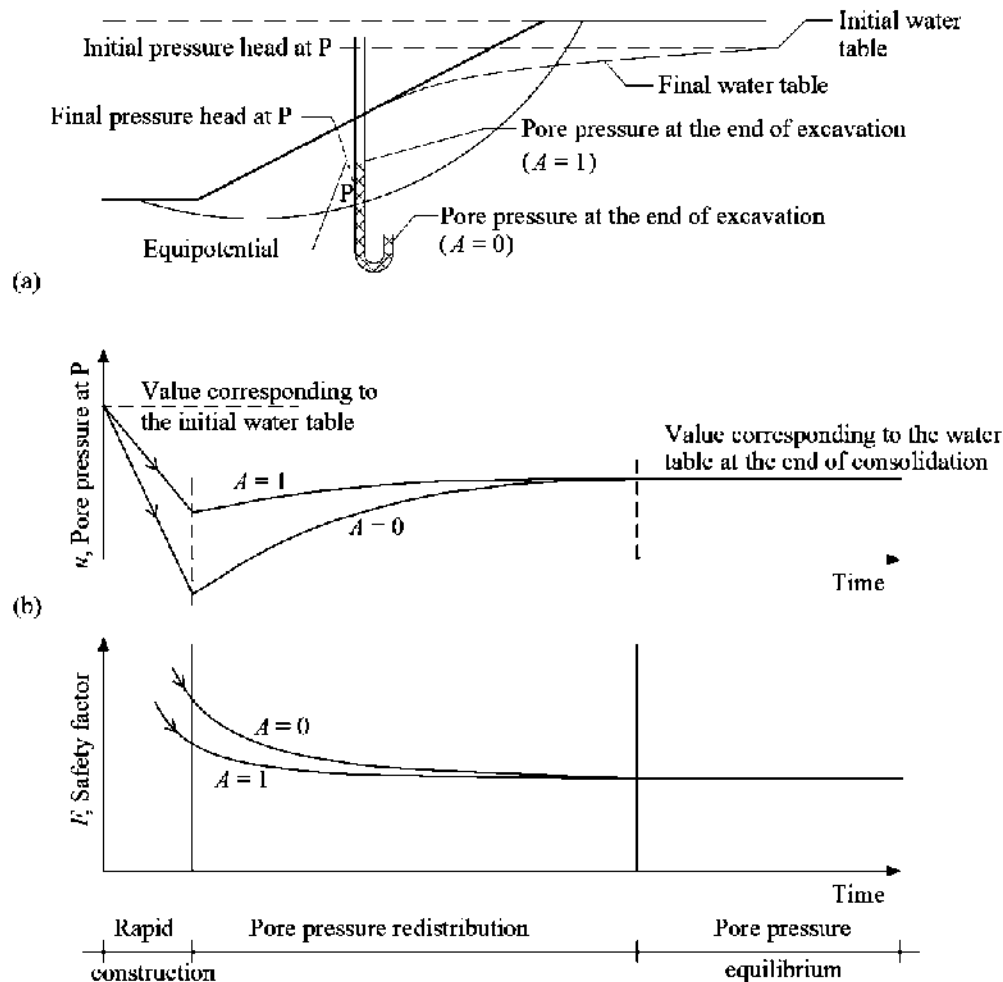


Figure 2. Sloped cut in clay: a) initial and final conditions of the water table and pore pressure at a generic point P at the end of the excavation; b) change in time of the pore water pressure at P and of the safety factor (adapted from Bishop & Bjerrum, 1960)

Figure 2 compares changes in quantities due to the excavation in clay deposit (a NC soil with $A=1$ or an OC soil with $A=0$, A being Skempton's pore pressure parameter) to form a cut slope, and the post-excavation phase when dissipation of excess pore water pressure takes place. These quantities, shown in Figure 2b, are the pore water pressure and factor of safety for a generalized slip failure of the excavated slope.

The main idea is that the factor of safety decreases progressively not only during but also after the completion of the excavation. During excavation, the loading is essentially applied under undrained conditions (rapid construction). The excess pore pressure within the soil mass close to the cut is the combined result of the drop in the mean total stress and the increase of the shear stress. The former induces negative excess pore pressure; the latter induces positive excess pore pressure in a NC clay and small positive or even negative excess pore pressure in a heavily OC clay. This explains why during the excavation the drop in the pore pressure is larger in the OC clay.

Then, the process of dissipation of the negative excess pore pressure starts. This is in fact a consolidation process, though involving changes in time of the variables opposite to those of the embankment construction.

Since pore water pressures in the vicinity of the cut are smaller than the ones in the mass far from the cut, the water starts gradually flowing towards the cut, the pore pressure increases, the effective stress decreases and so do the shear strength and the factor of safety, which reaches its minimum value in the long-term. Contrarily to the embankment case, the long-term pore water conditions are no longer hydrostatic, because the cut implies a change on the hydraulic boundary conditions. In the long-term, a steady-state flow of water towards the cut will be established.

Hence, the critical situation for the evaluation of the minimum safety factor for this loading situation (that is, the stability analyses) is the long-term, assuming drained conditions and working in effective stresses. The equilibrium pore pressures to be considered in the analyses are obtained from the corresponding steady-state flow net.

Table 1 contains a comparison between the two problems in terms of the change in stresses, induced strains, hydraulic conditions, ground surface movement, safety factors, stability analyses and other relevant issues. According to the experience of the first author, completing cell by cell the second and third columns of the table in the class is very stimulating and effective for the comprehension of this subject by the students.

1. Table 1. Comparison of features associated with embankments and cuts in clay (adapted from Matos Fernandes, 2020)

Item	Embankments	Cuts
Total mean stress increment	Increases	Decreases
Shear stress (under the embankment or behind the cut face)	Increases	Increases
Excess pore pressure, Δu	Positive	Negative
Soil type in which $ \Delta u $ is maximum	Normally consolidated	Heavily over-consolidated
Change of u with time (after the end of construction/excavation)	Decreases	Increases
Flow during consolidation	Directed outwards	Directed towards the excavation
Change of water content and void ratio with time	Decrease	Increase
Change of volumetric deformation with time	Positive (compression)	Negative (expansion)
Ground surface displacement	Settlement	Heave
Change with time of the mean effective stress and of the shear strength (after the end of construction/excavation)	Increase	Decrease
Change with time of the safety factor	Increases (post construction)	Decreases
Phase in which the stability analyses should be performed	End of construction	End of consolidation
Conditions for the stability analyses	Undrained	Drained
Approach in terms of stress for the stability analyses by the method of slices	Total stress	Effective stress
Strength parameters involved in the analyses	c_u , considering its change with depth	Effective strength parameters, c' and ϕ'
Other data items required for the analyses	Unit weight	Steady-state flow net; unit weight

3 Numerical simulation of the construction of an embankment on soft clay

3.1 Brief description of the models employed

In the present paper, two computer codes are used: (i) a finite element (f.e.) program capable of performing soil consolidation coupled analysis (Borges, 1995); (ii) a stability analysis program that uses the f.e. results.

The f.e. program uses the following theoretical hypotheses: a) plane strain conditions; b) coupled formulation of the flow and equilibrium equations, with soil constitutive relations formulated in effective stresses (Biot consolidation theory), applied both during the construction and the post-construction period; c) utilisation of the p - q - θ critical state model, which is an extension of the Modified Cam-Clay model into the 3D stress space using the Mohr-Coulomb failure criterion, to simulate the soil behaviour (Lewis & Schrefler, 1987; Britto & Gunn, 1987; Borges, 1995; Borges & Cardoso, 2001).

The stability is assessed, at any stage of the simulation, by the second computer program mentioned above, in which potential slip surfaces are generated and the respective overall safety factor is calculated, using the stress values provided by the f.e. analysis. Firstly, for each potential slip surface, the intersection points of the circle with the edges of the finite elements are determined. Then, the slip surface is divided into small line segments, each of them located inside of only one of the finite elements of the mesh. Afterwards, the average values of effective normal and shear stresses at each of those segments are computed, on the basis of the stress values in the Gauss points in the vicinity.

Thus, considering the slip circle divided into line segments, the overall safety factor, F , is computed through the equation:

$$F = \frac{\sum_{i=1}^N \tau_{fi} l_i}{\sum_{i=1}^N \tau_i l_i} \quad (1)$$

where τ_i is the acting shear stress at i -segment, τ_{fi} is the soil shear strength at i -segment, l_i is the i -segment length and N is the number of elements intersected by the slip surface. The soil shear strength, τ_{fi} is calculated by using the failure envelope equation, according to the p - q - θ critical state model. A large number of potential slip surfaces is analysed by the program, so that the most unfavourable slip circle is obtained, which corresponds to the smallest value of F calculated.

Note that, according to this procedure, the stability analysis is performed using effective stresses. This is possible because the stability computations are fed by the results of the f.e. simulations and, since mechanical-hydraulic coupled analyses are performed, effective stresses are obtained. Similar procedures were used by Borges & Cardoso (2001, 2002) to analyse the stability of geosynthetic-reinforced embankments on soft soils and by Borges (2024a, 2024b) to study the behaviour of embankments on soft soils reinforced with stone columns.

3.2 Presentation of the problem

The problem concerns a 2.0 m high symmetric embankment, with a very large longitudinal length, built on a 25 m thick saturated clay deposit lying on a rigid and impermeable stratum (Figure 3). The clay is moderately over-consolidated to the depth of 4 m (superficial OC crust) and normally consolidated from 4 to 25 m. The width of the embankment crest is 13.6 m. The water level is assumed at the ground surface.

Drained analysis is considered in the embankment material while a fully mechanical-hydraulic coupled analysis is adopted for the clay. The construction of the embankment is modelled by adding layers of elements at a uniform rate and is completed in 7 days.

The constitutive behaviour of the soils (clay and embankment fill material) is simulated by the p - q - θ critical state model whose parameters are shown in Table 2 (λ , slope of normal consolidation line and critical state line; k , slope of swelling and recompression line; N , specific volume of normally consolidated soil at mean normal effective stress equal to 1 kPa; Γ , specific volume of soil on the critical

state line at mean normal effective stress equal to 1 kPa). Other geotechnical parameters are also indicated in Table 2: γ , unit weight; ϕ' , angle of friction defined in effective stresses; ν' , Poisson's ratio for drained loading; k_h and k_v , coefficients of permeability in horizontal and vertical directions. The undrained shear strength (c_u) of the clay, also presented in Table 3, is obtained from the other parameters of the model, applying equations of the Critical State Soil Mechanics, as explained in detail by Britto & Gunn (1987) and Borges (2024a, b).

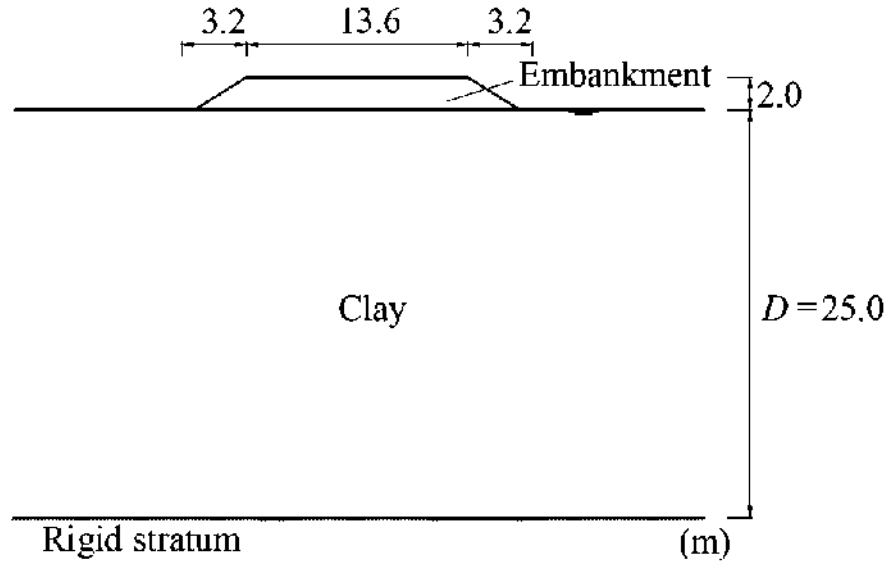


Figure 3. Cross section of the embankment on soft soil problem

The parameters of the clay are similar to those considered by Finno et al. (1991) of a soft ground in Chicago, USA. The values adopted for the embankment fill material are the same as those used by Borges & Cardoso (2001).

The assumed over-consolidation to the depth of 4 m intends to simulate a superficial crust, which is typical of alluvial clayey deposits (Lutenegger, 1995). This crust is formed by the seasonal cycles of the groundwater level, which is very close to the surface but not always at the same position. In the soil horizon above the water table, the capillarity develops negative pore pressures (suction). Since the soil is very fine, these negative pore pressures are high (in absolute values), which implies high interparticle forces. So, the variations of the groundwater level are equivalent, in terms of stresses, to loading-unloading cycles. This creates a thin OC superficial layer which is often called desiccated crust. The engineering relevance of this crust is paramount, since it makes feasible the construction of embankments and other structures founded at the surface of the deposit. According to Bjerrum (1973), the thickness of this crust may range from as little as 1 to 3 m to as much as 6 to 8 m, depending on the site conditions.

2. Table 2. Geotechnical parameters of the clay and of the embankment fill

	γ (kN/m ³)	ν' (-)	ϕ' (°)	c' (kPa)	k_h (m/s)	k_v (m/s)	p - q - θ critical state model			
							λ	k	N	Γ
Clay	16	0.25	26	0	10^{-9}	10^{-9}	0.18	0.025	3.158	3.050
Embankment	20	0.30	35	0	-	-	0.03	0.005	1.817	1.800

3. Table 3. Undrained shear strength (c_u) of the clay

Depth, z (m)	c_u (kPa)
0	13.0
$0 \leq z \leq 4$	13.0 - 6.53 (*)
4	6.53
$4 \leq z$	$1.633z$

*Linear variation

3.3 Discussion of the results

A finite element analysis provides a large amount of results concerning displacements, stresses, pore pressures and other quantities. Just a small portion of that information is presented herein.

Figure 4 illustrates the surface vertical displacements at the completion of the embankment construction and at the end of consolidation. Since the construction is completed in a very short period, the volumetric strains of the foundation soil are practically null. Then, at the end of construction the settlement under the embankment must be compensated by the upward vertical displacements in the vicinity. The ensuing consolidation process produces positive volumetric (compression) strains, inducing surface settlements.

For the central point of the base of the embankment the consolidation settlement is about twice the immediate settlement. The change in time of the settlement of this point is depicted in Figure 5. The progressive reduction of the settlement rate during the consolidation reveals a pattern similar to that of the classical theory of consolidation of Terzaghi.

In theoretical terms, the consolidation process is never concluded. In practice, it can be seen that, say, beyond 600 months (50 years) the change in the surface settlements is negligible. This very large time period is a consequence, beyond the very low permeability of the clay soil, of the large thickness of the layer (25 m) and of the assumption of an impermeable lower boundary.

Figure 6 presents the horizontal displacements under the embankment toe ($x = 10$ m), at the end of construction and at the end of consolidation. It can be seen that the incremental displacements during consolidation are quite small, in comparison with the vertical displacements that occur in the same time period. That is, during consolidation the foundation soil is loaded in conditions that are close to a confined loading, similar to the conditions prevailing in an oedometer test. This fact is the base of the well-known simplified method of Skempton & Bjerrum (1957) for the calculation, in similar cases, of the consolidation settlement using the compressibility parameters provided by the oedometer test.

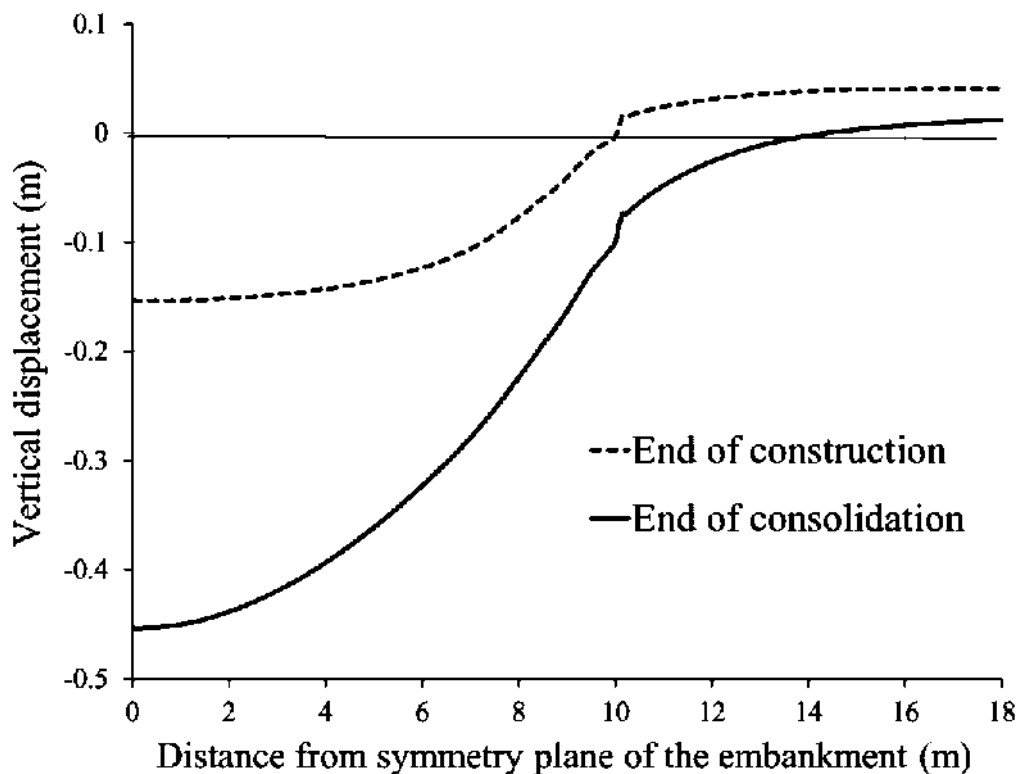


Figure 4. Vertical displacements of ground surface at the end of construction (7th day) and at the end of consolidation

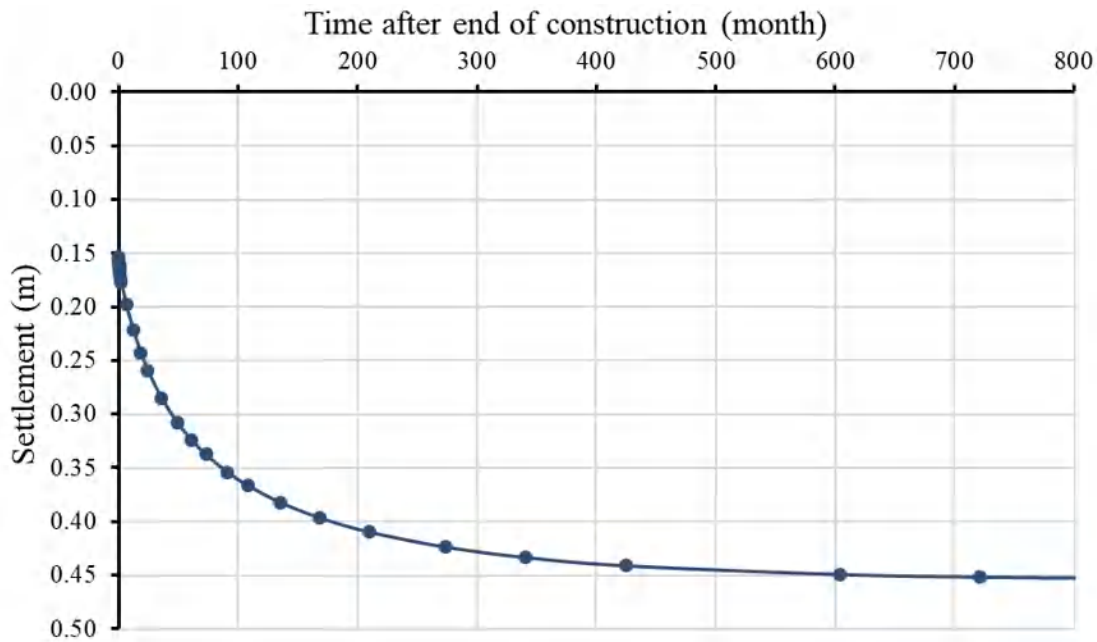


Figure 5. Settlement versus time at midpoint of the embankment's base

A more detailed observation of Figure 6 reveals that during consolidation the horizontal displacements diminish in the OC superficial crust and increase in the lower NC soil mass. The superficial OC crust is (elastically) reloaded, and experiences volumetric positive strains (compression), which explain the volume reduction, and therefore inward horizontal displacements. On the other hand, the lower NC mass is loaded in virgin compression, exhibiting an elastoplastic behaviour. In addition to the volumetric strains, which induce inward horizontal displacements, some plastic deviatoric strains arise, provoking outward horizontal displacements. When this effect is stronger than the former, like in this case, the resulting horizontal displacements increase during the consolidation process.

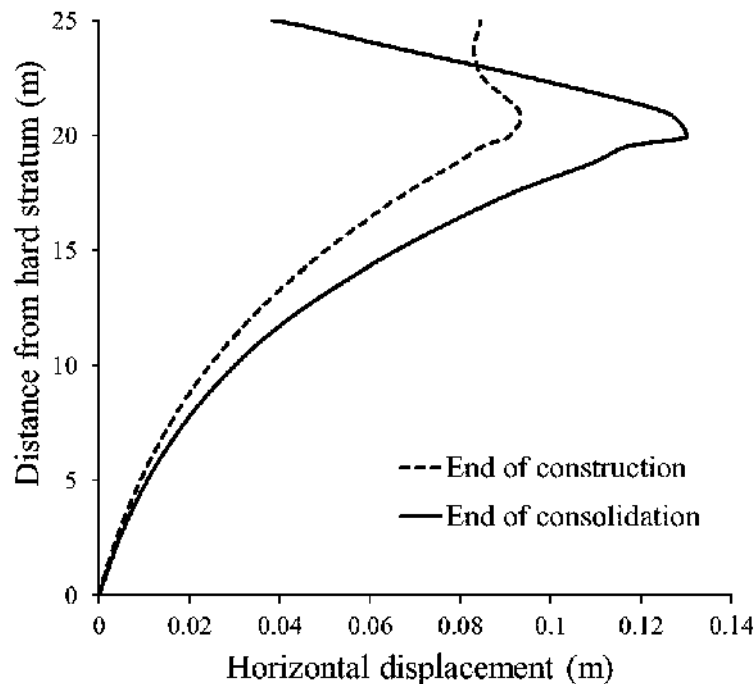


Figure 6. Horizontal displacements under the embankment toe ($x = 10$ m), at the end of construction (7th day) and at the end of consolidation

The distribution of the excess pore pressure in the foundation soil at the end of the construction and for three stages of the consolidation process, can be observed in Figure 7. The distribution for the end of construction reveals a more complex pattern, resulting from the influence of the over-consolidated crust. This effect vanishes during consolidation. As might be expected, the excess pore pressure reduces with the horizontal and vertical distances from the central point of the embankment base. Besides, since the clay is assumed isotropic in terms of permeability, the isolines of Δu are perpendicular to the impermeable lower boundary of the clay deposit. It should be noted that the isolines of Δu coincide with the isolines of total head (equipotential lines), since the initial value of total head (before construction) is constant in the ground, i.e. it has the same value at all points of the saturated clay (hydrostatic condition).

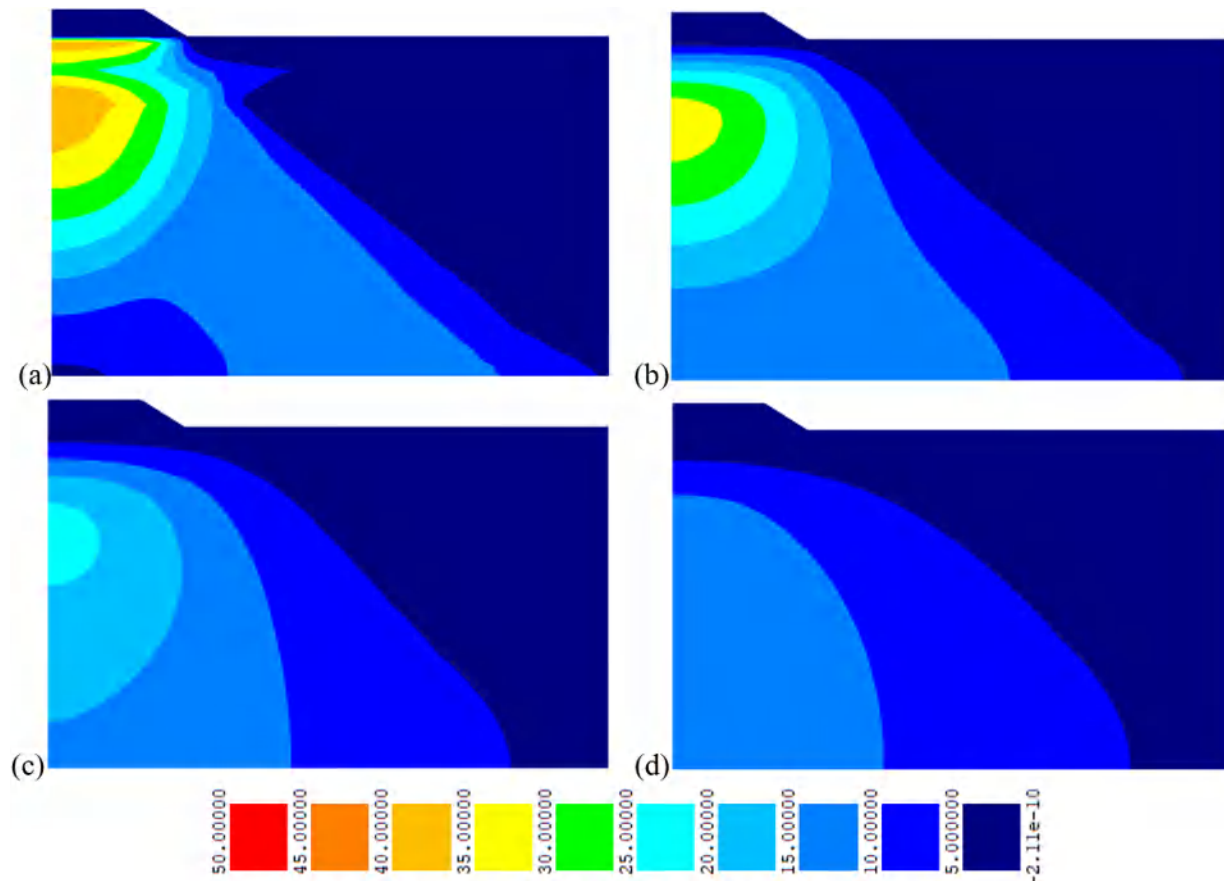


Figure 7. Distribution of excess pore pressure (Δu) in the clay deposit: a) end of construction (7th day) ($\Delta u_{max} = 39.7$ kPa); b) 6 months after end of construction ($\Delta u_{max} = 32.1$ kPa); c) 2 years after end of construction ($\Delta u_{max} = 21.1$ kPa); d) 5 years after end of construction ($\Delta u_{max} = 13.6$ kPa)

On the basis of the distribution of the pore pressure and of the total and effective stresses for each time after the construction, and by applying the procedure described in Section 3.1 above, the safety factor against a general failure was computed. The results, presented in Figure 8, confirm that the critical situation in terms of stability is the end of construction and that a substantial increase of the safety factor occurs during consolidation.

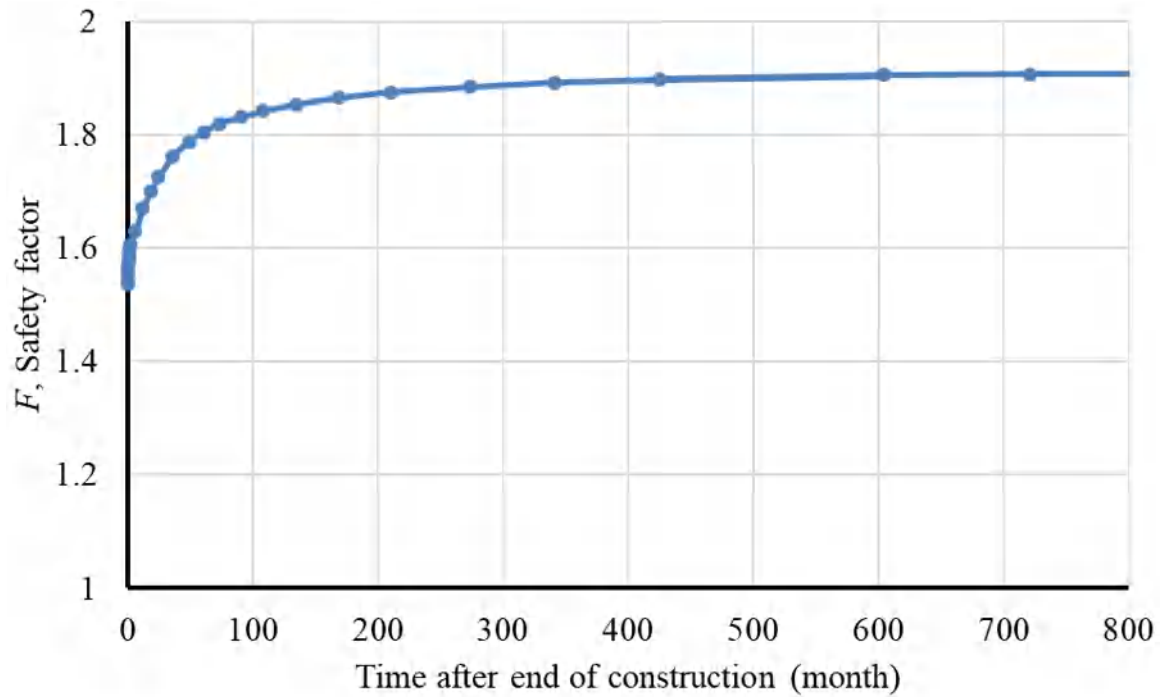


Figure 8. Safety factor (F) versus time after the end of construction

Finally, the critical slip surfaces (minimum safety factor) for the end of construction and for the end of consolidation are shown in Figure 9. It can be seen that these slip surfaces are not coincident, with the one for the end of consolidation encompassing a larger volume of the foundation soil further away from the embankment. This is reasonable because consolidation improves more the resistance in the soil mass underneath the loaded area compared to the soil further away.

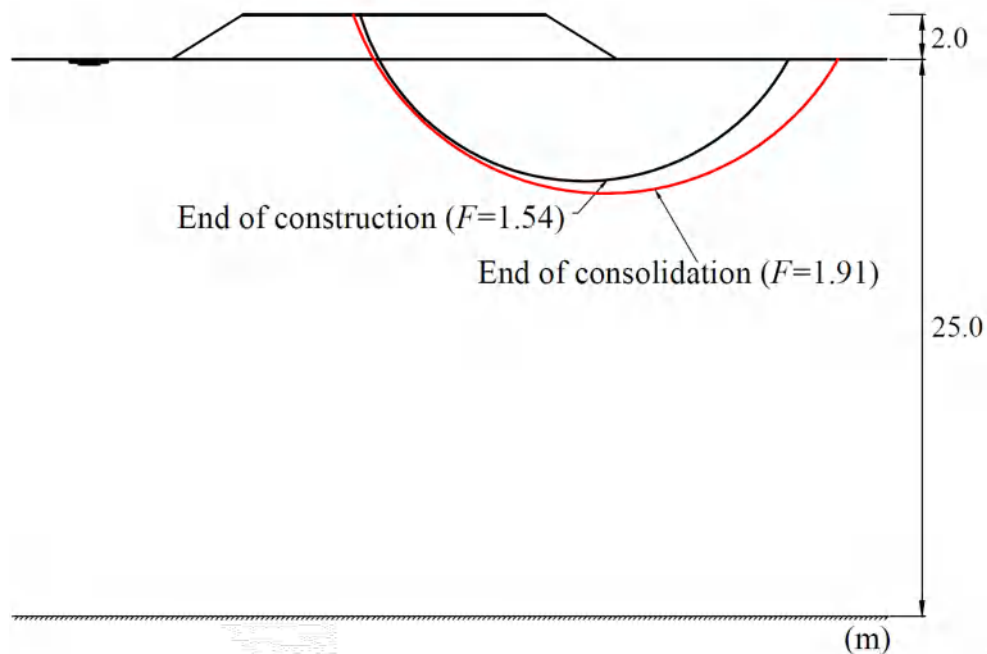


Figure 9. Critical slip surfaces and respective overall safety factor values (F) at the end of construction and at the end of consolidation

4 Concluding remarks

The paper revisits two classical figures (Bishop & Bjerrum, 1960), describing two common and relevant geotechnical works: the construction of embankments on soft clay (loading) and the excavation of unsupported sloped cuts in clays (unloading). These conceptual figures are elaborated upon with in-depth commentary and a table summarizing and contrasting trends for the mechanical and hydraulic phenomena triggered by the construction of these two works, thus touching on most key issues of soil behaviour. The loading case is supplemented with numerical simulation results (immediate and consolidation surface settlements and horizontal displacements in depth, excess pore pressures and their change in time, and safety factor against a general failure and its change in time) that confirm the conceptual stability trends at a point and offer insights into the behaviour of the entire soil mass.

Since the discussion is not anymore restricted to shear strength parameters in laboratory-controlled conditions (fully drained or fully undrained), but extends to the resistance and stability of a large soil mass over time, it can be said that this subject is particularly suitable not only as an epilogue of a basic course on soil mechanics (Soil Mechanics or Soil Mechanics 1), but also as an inaugural class of a course on soil engineering (Soil Mechanics 2 or Geotechnical Engineering).

References

- Bishop, A. W., Bjerrum, L. (1960). The relevance of the triaxial test to the solution of stability problems. *Proceedings of the Conference on Shear Strength of Cohesive Soils*, ASCE, Boulder, CO, 437–501.
- Bjerrum, L. (1973). Problems of Soil Mechanics and Construction on Soft Clays and Structurally Unstable Soil (Collapsible, Expansive and Others). In *Proc., 8th International Conference on Soil Mechanics and Foundation Engineering*, 3: 111-159.
- Borges, J. L. (1995). Geosynthetic reinforced embankments on soft soils. Analysis and design. PhD Thesis, University of Porto (in Portuguese). <http://hdl.handle.net/10216/11931>
- Borges, J. L., Cardoso, A. S. (2001). Structural behaviour and parametric study of reinforced embankments on soft clays. *Computers and Geotechnics*, 28(3), 209-233. [https://doi.org/10.1016/S0266-352X\(00\)00021-5](https://doi.org/10.1016/S0266-352X(00)00021-5)
- Borges, J. L., Cardoso, A. S. (2002). Overall stability of geosynthetic reinforced embankments on soft soils. *Geotextiles and Geomembranes*, 20(6): 395-421. [https://doi.org/10.1016/S0266-1144\(02\)00014-6](https://doi.org/10.1016/S0266-1144(02)00014-6)
- Borges, J. L. (2024a). Geosynthetic-Reinforced and Stone Column-Supported Embankments: Numerical and Stability Study. *Geotechnical and Geological Engineering*, 42:1933–1955. <https://doi.org/10.1007/s10706-023-02654-8>
- Borges, J. L. (2024b). Floating stone column-supported embankments on soft soils: numerical study incorporating stability analysis and basal reinforcement with geosynthetic. *Soils and Rocks*, 47(4): e2024006023. <https://doi.org/10.28927/SR.2024.006023>
- Britto, A. M., Gunn, M. J. (1987). *Critical Soil Mechanics via Finite Elements*. Ellis Horwood Limited, England.
- Finno, R. J., Harahap, I. S., Sabatini, P. J. (1991). Analysis of braced excavations with coupled finite element formulations. *Computers and Geotechnics*, 12(2): 91-114. [https://doi.org/10.1016/0266-352X\(91\)90001-V](https://doi.org/10.1016/0266-352X(91)90001-V)
- Lambe, T. W., Whitman, R. V. (1979). *Soil Mechanics*, SI Version. John Wiley & Sons.
- Lewis, R. W., Schrefler, B. A. (1987). *The Finite Element Method in the Deformation and Consolidation of Porous Media*. John Wiley & Sons.
- Lutenegger, A. (1995). Geotechnical behavior of overconsolidated surficial clay crusts. *Transportation Research Record*, 1479, National Academy Press, Washington, D.C., 61-74.
- Matos Fernandes, M. (2020). *Analysis and Design of Geotechnical Structures*, CRC Press, 731 p., DOI: <https://doi.org/10.1201/9780429398452>.

Authors' bios

Manuel Matos Fernandes, University of Porto (Portugal)

Manuel Matos Fernandes was Full Professor at the Faculty of Engineering of University of Porto (FEUP). After his retirement in 2023, he was declared Emeritus Professor by the Senate of the University. His main areas of interest are numerical modelling of geotechnical works, deep excavations, education in Geotechnics and History of Construction. He was Director of the Department of Civil Engineering (2000-03 and 2009-15), Coordinator of the Construction Study Centre (2009-14), a R&D unit with 50 PhD staff, and member of the General Council of the University of Porto (2013-17). He is the author of textbooks on Soil Mechanics and Geotechnical Engineering internationally published. In 2013 he received the Prize in Pedagogic Excellency of FEUP. He was President of the Portuguese Geotechnical Society (2016-20) and editor of the journals *Geotecnia* (2000-04) and *Soil and Rocks* (2012-16). He works as a consultant for the design and construction of geotechnical structures.

José L. Borges, University of Porto (Portugal)

PhD in Civil Engineering in 1996 by Faculty of Engineering of University of Porto (FEUP), Degree in Civil Engineering in 1982 by FEUP. Is Assistant Professor in FEUP and Researcher of the CONSTRUCT - Institute of R&D in Structures and Construction. Author of 93 scientific and pedagogical publications, including 24 articles in scientific journals. Member of the organizing committees of 7 scientific conferences. Supervised 1 PhD thesis. Supervised 26 MSc dissertations. Develops research in the following main areas: Civil Engineering; Geotechnics. Was Director of the Civil Engineering Course (pre-Bologna) of FEUP (1997-1999); Member of the Pedagogical Council of FEUP (1997-1999); Member of the Executive Committee of the Department of Civil Engineering of FEUP (1997-1999 and 2004-2015); Member of the Council of the Department of Civil Engineering of FEUP (1991-1992; 1996-2002; 2010-2014); Designer of structures at the companies "Soares da Costa, SA" (1983) and "FASE - Estudos e Projectos SA" (1984-1987).

Marina Pantazidou, National Technical University of Athens (Greece)

Marina Pantazidou is an associate professor at the Civil Engineering School of the National Technical University of Athens, Greece. Apart from university appointments in the US and Greece, her professional experience also includes work in hazardous waste consulting. Her research topics are drawn from environmental geotechnics and engineering education. She is author of 100 publications, 25 of which on geotechnical engineering education topics. She has been a guest editor for two special issues on geotechnical engineering education, one on case studies developed for geotechnical engineering instruction. She has been actively involved with the Hellenic Society for Soil Mechanics and Geotechnical Engineering (secretary general 2012-2015 and board member 2015 -) and the ISSMGE Technical Committee TC306 on Geo-engineering Education (core member 2010-2013, vice chair 2013-2017, chair 2017 -). She chaired the ISSMGE Int. Conf. on Geotechnical Engineering Education GEE2020, (streamed from) Athens, Greece, June 23-25.

Integrating advanced computational tools into geotechnical engineering education: an example of transformative learning through digital technology

H. Moghaddasi¹, M. Moradi¹, A. Tarantino¹ & B. Ogwezi²

¹University of Strathclyde, Department of Civil and Environmental Engineering, Glasgow, UK
hamed.moghaddasi@strath.ac.uk, maziar.moradi@strath.ac.uk, alessandro.tarantino@strath.ac.uk

²Ansys, Inc., Cambridge, UK
Bridget.Ogwezi@ansys.com

ABSTRACT: This work aims to demonstrate how cutting-edge technology in Ansys, a FEM/CFD software with real-time simulations and visualizations, can be integrated into undergraduate geotechnical engineering modules. The software was first introduced in the 2nd year Soil Mechanics module as a virtual laboratory for teaching seepage theory in soil mechanics. Through this virtual laboratory, students were able to better visualise how water flows through soils, providing a 'virtual' hands-on experience that complements effectively learning via traditional lectures or textbook reading. Key 'educational' features of Ansys, including the intuitive user interface in Ansys Discovery and the ability to mask the FEM mesh, played a crucial role in the success of these virtual laboratories. These features allowed undergraduate students, even without prior FEM experience, to effectively grasp the main learning outcomes of the module. In this paper, the educational effectiveness of this advanced technology is evaluated through the students' academic perception, engagement level, and performance. A comparison is made between the traditional delivery of soil mechanics content and the technology-assisted approach. Using the educational insights gained, a plan is outlined for integrating Ansys technology into broader soil mechanics and geotechnical engineering topics, such as advanced foundation design and slope stability analysis.

Keywords: Digitally-enhanced learning, Numerical modelling, Soil Mechanics

1 Introduction

Several studies have focused on integrating digitally-assisted into the existing geotechnical engineering curriculum (Jaksa, 2020; Rehman, 2023). Key advancements include the use of virtual laboratory testing (Airey et al., 2012; Ledesma Villalba et al., 2022; Allawi, 2023), online learning platforms (Rehman, 2023), and most notably computer-aided instruction (Toll & Barr, 1998; Oliver & Oliphant, 1999; Isik & Cabalar, 2018; Allawi, 2011; Yin et al., 2022). One of the major benefits of this trend is the ability to enhance students' visualization and problem-solving skills, enabling them to tackle challenges that extend beyond traditional theoretical frameworks presented in textbooks. Recent technological advancements in geotechnical engineering, such as numerical simulations and visualizations of complex geo-structures, have progressed faster than the development of existing educational resources. This is particularly significant for undergraduate students, who primarily focus on theoretical knowledge in geotechnical engineering modules. While fundamental analytical and conceptual models remain essential for teaching the core concepts of geotechnical engineering, developing a curriculum that integrates computer-aided approaches early in the learning process is crucial for the success of future geotechnical engineers.

Integrating computer-based methods into geotechnical engineering modules offers affordable educational tools, better prepares students for real-world industry challenges, and enhances the

effectiveness of online learning by providing flexible and interactive experiences. Early educational platforms for teaching geotechnical engineering relied on simple, yet effective, homemade software to cover fundamental topics such as soil classification (Isik & Cabalar, 2018), seepage in soil (Allawi, 2011), slope stability (Yin et al., 2022), foundation design (Toll & Barr, 1998) and effective stress concept (Oliver & Oliphant, 1999). While these tools are well-suited for their intended purpose and offer immediate pedagogical benefits with minimal prior knowledge required, their use is limited in terms of scope of engineering applications. They were not easily adaptable to real-world scenarios or complex geotechnical labs and often become outdated, falling behind the latest advancements in the field (Houston, 2019). The integration of modern commercial geotechnical software, into teaching and learning can help address several educational challenges, fostering greater student engagement and enhancing graduates' employability (Pinho-Lopes, 2012; Szavits-Nossan, 2012). However, despite these advantages, the complexity of such software, particularly its basic user interface for early-year students, the limited availability of qualified instructors, and the lack of widespread free access to these tools remain a significant barrier to their broader adoption in geotechnical engineering education.

The purpose of this work is to integrate a comprehensive engineering software package, Ansys, into the teaching of the Soil Mechanics module at the University of Strathclyde to enhance students' understanding through computer-aided learning. New features of Ansys technology, such as Ansys Discovery, are integrated into the existing curriculum of the Soil Mechanics module to improve quantitative and qualitative learning outcomes and to expose students to industry-standard tools. The future goal is to integrate Ansys tools in other civil engineering modules to ensure that students are thoroughly equipped with technology skills to tackle real-world challenges in the civil engineering field.

2 Methodology

This study evaluates the outcomes of integrating a technology-enhanced framework into the existing Civil and Environmental Engineering (CEE) degree programs at the University of Strathclyde. The framework was introduced in the Soil Mechanics module, a 20-credit, second-year module offered within both the Bachelor of Engineering (BEng) and Master of Engineering (MEng) programs. The BEng program is completed over four years with 480 credits requirement, while the MEng program spans five years with 600 credits requirement. Students enrolled in the BEng pathway are eligible to transfer to the MEng program if they achieve a credit-weighted average above 60%. Typically, approximately 100 students enrol in the BEng program each year. In the second year, students must successfully complete six compulsory modules — each worth 20 credits — to progress to the third year. Instruction is primarily delivered through face-to-face teaching, with online classes permitted under certain circumstances. The total workload for the Soil Mechanics module is 200 hours, which includes 32 hours of lectures, 26 hours of tutorials, 10 hours of laboratory sessions, 14 hours of coursework, and 118 hours of independent study, over 12 weeks. In Semester 1 of the Soil Mechanics module, two key learning outcomes are established. First, students are expected to develop an understanding of groundwater flow and the ability to predict pore-water pressures under the steady-state conditions. Second, they should grasp the concept of effective stress in saturated soils and be able to analyse the soil stress state under both hydraulic and mechanical loading.

Although the module spans two semesters, the technology-enhanced framework was implemented only during semester one, specifically in one of the laboratory sessions. In the previous academic year (2023/24), conventional teaching methods were used for this laboratory session, providing a point of comparison for evaluating the effectiveness of the new approach. For this initial trial, the assessment structure remained unchanged from the prior year: 20% of the final grade was based on online quizzes, 20% on laboratory assessments, and 60% on the final exam. The computer laboratory component contributed 10% to the overall grade within the laboratory assessment category. Students' performance was assessed through reports submitted via the University of Strathclyde's online learning platform. The following sections detail the original and revised laboratory sessions and provide a comparative analysis. The effectiveness of the newly implemented framework will then be evaluated.

3 Existing laboratory for Soil Mechanics module

The Soil Mechanics module is a core component of the early-stage curriculum in civil and environmental engineering undergraduate programs. Its primary goal is to introduce students to the physical, hydraulic, and mechanical behaviour of soils, focusing on their application in construction and landscaping projects. At the University of Strathclyde, traditional teaching methods, including theoretical lectures and hands-on laboratory and computer sessions, are employed to deliver this module over two semesters. The prerequisite for this module is the 'Fundamentals of Civil Engineering' module, where students are introduced to basic concepts related to soils and rock material characterisation during their first academic year. In the first semester of the second year, students participated in computer laboratory sessions where they used a simple finite difference spreadsheet, known as Seepage_CSM8, to calculate seepage around a sheet pile wall. This laboratory session aligns with the first learning objective, where students learn to predict pore-water pressures under steady-state conditions. They first learn the theoretical foundations of the finite difference method (FDM) applied to the solution of the Laplace equation in the class and then view a training video on Seepage_CSM8 prior to the laboratory sessions, following a flipped classroom approach (see Moghaddasi et al., 2024). The theoretical framework of the FDM was taught during a dedicated two-hour lecture, followed by a tutorial session demonstrating hand calculations using the FDM approach. This laboratory also includes manual calculations of seepage problems using the flow net approach, which is then compared with the numerical solutions obtained from Seepage_CSM8. The students compare their FDM solution with the results obtained through hand calculations and reflect on the reasons for any discrepancies. An example of a submitted assignment is shown in Figure 1, where students use both hand-calculations and spreadsheet software (traditional approach). Since the software is based on a spreadsheet (MS Excel), students are already familiar with the user interface and require minimal assistance for training of the spreadsheet. However, feedback from the instructor indicated that the spreadsheet software was not able to effectively visualize flow lines or simulate problems with large dimensions or finer mesh. Student feedback also highlighted difficulties in detecting errors during mesh refinement, particularly when incorrect equations were entered into the Excel cells. Additionally, students reported frequent spreadsheet crashes while solving flow equations iteratively. Another notable issue was that Seepage_CSM8 is designed solely for solving uncoupled flow problems (no deformation analysis) and can only handle 2D cases.

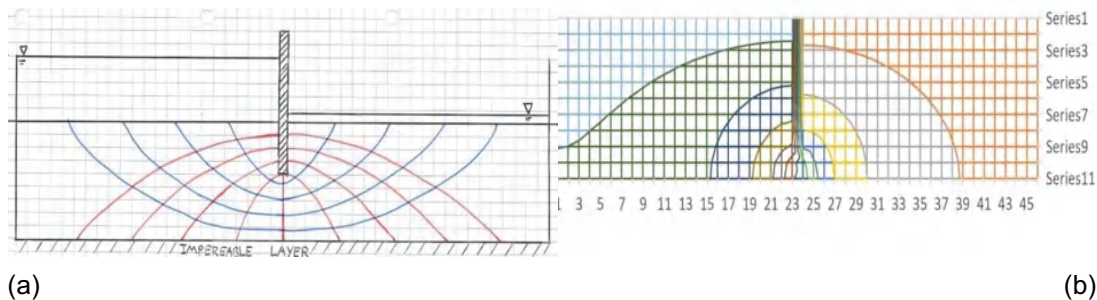


Figure 1. Examples of submitted students' work using (a) flow net approach and (b) Seepage_CSM8 (traditional approach)

4 Revised laboratory for 'Soil Mechanics' module

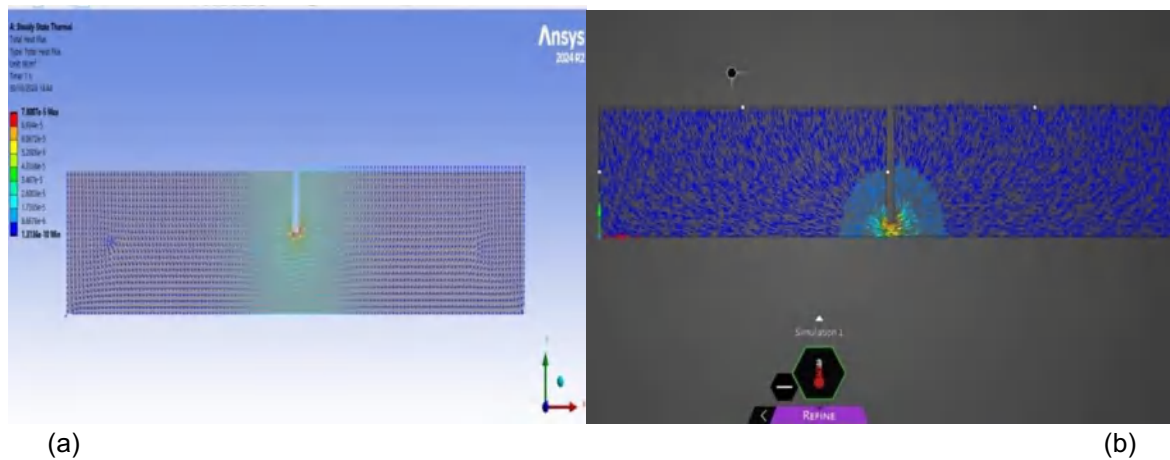
Within a joint collaboration between the University of Strathclyde and the Ansys company, a computer-aided learning framework was established to integrate Ansys technologies in the existing Civil Engineering undergraduate curriculum offered by the department of Civil and Environmental Engineering. This is part of an Ansys-funded curriculum program designed to support accredited educational institutions in developing computer-aided programs using Ansys technology. Ansys is a powerful software suite for finite element analysis (FEA) and computational fluid dynamics (CFD), essential for simulating complex civil engineering problems. Its wide range of simulations across various physical phenomena and materials, combined with advanced post-processing and visualization tools, make it an invaluable resource for teaching. Due to the significant limitations of Seepage_CSM8, Ansys technology was introduced for the first time in the computer laboratory of the Soil Mechanics module in the 2024/25 academic year. To support students, an Ansys educational page was created on MyPlace

(the Strathclyde University portal for teaching and learning), and a series of training videos were recorded at the Strathclyde Professional Studies, supplemented by additional resources from the Ansys educational website. Since second-year students are not yet familiar with the basics of FEM for solving flow equations, a brief lecture was dedicated to explaining how the 2D Laplace equation can be solved using FEM. As in the previous teaching round, a flipped classroom approach was utilized, incorporating several pre-recorded ANSYS videos to support students prior to the computer laboratory sessions. During the laboratory sessions, students were encouraged to replicate the procedures demonstrated in the videos for a typical seepage problem. After the sessions, students applied their learning to solve an actual example provided in the laboratory handout. Similar to the previous teaching round, hand-calculation using flow net approach was part of the laboratory reports submitted by students. The students compare their FEM results with those derived from hand calculations and analyze the reasons for any discrepancies. Additionally, there is a reflection section where students document the assumptions and limitations of both the hand calculations and numerical results. It is important to note that students worked in groups of approximately four members during all laboratory sessions. In the live laboratory classes, students were instructed to replicate the model demonstrated in the training videos. After the sessions, students held group meetings to focus specifically on the laboratory problem and collaborate on their work.

While Ansys APDL does offer solutions for flow in porous media, it was decided not to use this package for teaching due to its relatively complex user interface and the software's complexity not suited for second-year CEE students without prior FEM knowledge. In contrast, Ansys Workbench and the newly developed Ansys Discovery were considered as most suitable options. Due to minimal prior FEM knowledge, undergraduate students may struggle with advanced topics like mesh dependency, which could negatively affect their perception of basic FEM usage. Specifically, Ansys Discovery is particularly well-suited for teaching first- and second-year students due to its user-friendly interface, which simplifies the learning process. Its ability to provide instant solutions to problems, along with the integration of FEM without requiring students to interact with the underlying mesh, makes it an effective tool for early year engineering education. This approach not only enhances students' creativity but also helps them develop stronger engineering judgment and a more expansive vision of problem-solving in their field (Wirth et al., 2017). The advantage of ANSYS Workbench is that it integrates multiple physics, such as structural analysis, fluid dynamics, and soil analysis, allowing for their interaction within real-world problems to provide comprehensive solutions. A crucial aspect of teaching FEM to students with no prior knowledge is to start with simple examples that have known analytical solutions. One such example is demonstrated in a training video, where students observe a 1D bar under axial loading solved through hand calculations, ANSYS numerical methods, and an analytical closed-form solution. Although this example is not related to seepage problems, it effectively helps students understand the complex concept of FEM. A comparison between the existing laboratory sessions taught during the 2023/24 academic year and the revised laboratory session is provided in Table 1. One challenge in using Ansys Discovery or Ansys Workbench was that simulation of flow in porous media was not directly available in these packages. To address this, an analogy was drawn between the governing equations for total head variation in soils and temperature variations. Due to the mathematical similarities (both processes are governed by the same 'diffusion' equation), thermal analysis techniques were used to simulate the flow solution. While part of the previous laboratory, which involved hand calculations using the flow net approach, was retained in the revised sessions, Seepage_CSM8 was replaced by Ansys Workbench and Ansys Discovery. An example of the simulated flow results submitted by students using Ansys Workbench and Ansys Discovery is shown in Figure 2. In terms of the effort required from instructors to implement the revised laboratory session, it is important to note that learning new software can be demanding not only for students but also for instructors. To support instructors, a comprehensive and detailed guide has been developed and will be made publicly available through ANSYS educational resources, enabling its use by educators across various CEE programs.

Table 1. The summary of key differences and similarities across two teaching rounds

	Computer laboratory in 2023/24	Computer laboratory in 2024/25
Similarities	❖ The hand-calculation using flow net approach ❖ 10% assessment weight ❖ Numerical solutions included ❖ Flipped classroom approach used	❖ The hand-calculation using flow net approach ❖ 10% assessment weight ❖ Numerical solutions included ❖ Flipped classroom approach used
Differences	• FDM is easily teachable to students with minimal prior knowledge • 2D FDM solution using spreadsheet • Unable to solve 3D problems • Poor in visualisation and troubleshooting • Learning outcomes limited to the scope of laboratory sessions	• FEM is challenging for students to grasp without strong foundational knowledge • 2D FEM solution using Ansys workbench • 3D FEM solution using Ansys Discovery • Instant solutions with strong visualisations capacity • The skills learnt can be used in other CEE area

**Figure 2. The example of submitted students' work (revised approach) using a) Ansys Workbench b) Ansys Discovery**

5 Results and discussion

The effectiveness of the new approach to enhance the teaching and learning experience was evaluated by comparing key performance indicators across two academic years. These indicators include student engagement, academic achievements, and overall perceptions of the learning process. It is important to note that 101 students participated in the academic year 2023/24 module with the previous computer laboratory design, whereas 118 students were registered to the 2024/25 module, which featured the revised virtual laboratory sessions. The number of students submitting a work for this assessment was 89 in the academic year 2023/24 compared to 111 in the academic year 2024/25. In order to determine student satisfaction, two anonymous modules evaluation survey have been employed. The first survey was conducted by the university to obtain the overall satisfactions of students about 'Soil Mechanics' class and its results are depicted in Figure 3. The survey was conducted at the end of Semester 1, after students received feedback on their computer laboratory sessions, but before their final exam marks were issued. Around 15% participation rate was recorded in both the 2023/24 and 2024/25 surveys. During the 2024/25 academic year, a small number of students expressed dissatisfaction or indifference towards the class organization and available learning resources. This could be due to the delayed release of laboratory group lists and the late posting of lecture notes for the FEM section. Additionally, some students may require further support with the theoretical aspects of FEM, as this method was only introduced in a single lecture session. Overall, the number of highly satisfied students in the 2024/25 academic year significantly increased compared to the academic year 2023/24, particularly in key areas such as the availability of resources. This improvement is related the computer laboratory added in the 2024/25 academic year, the only new resource introduced in the overall class.

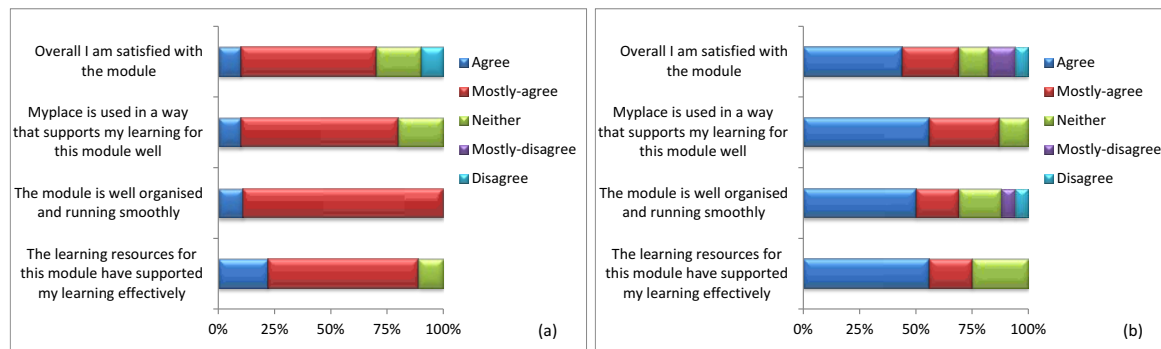


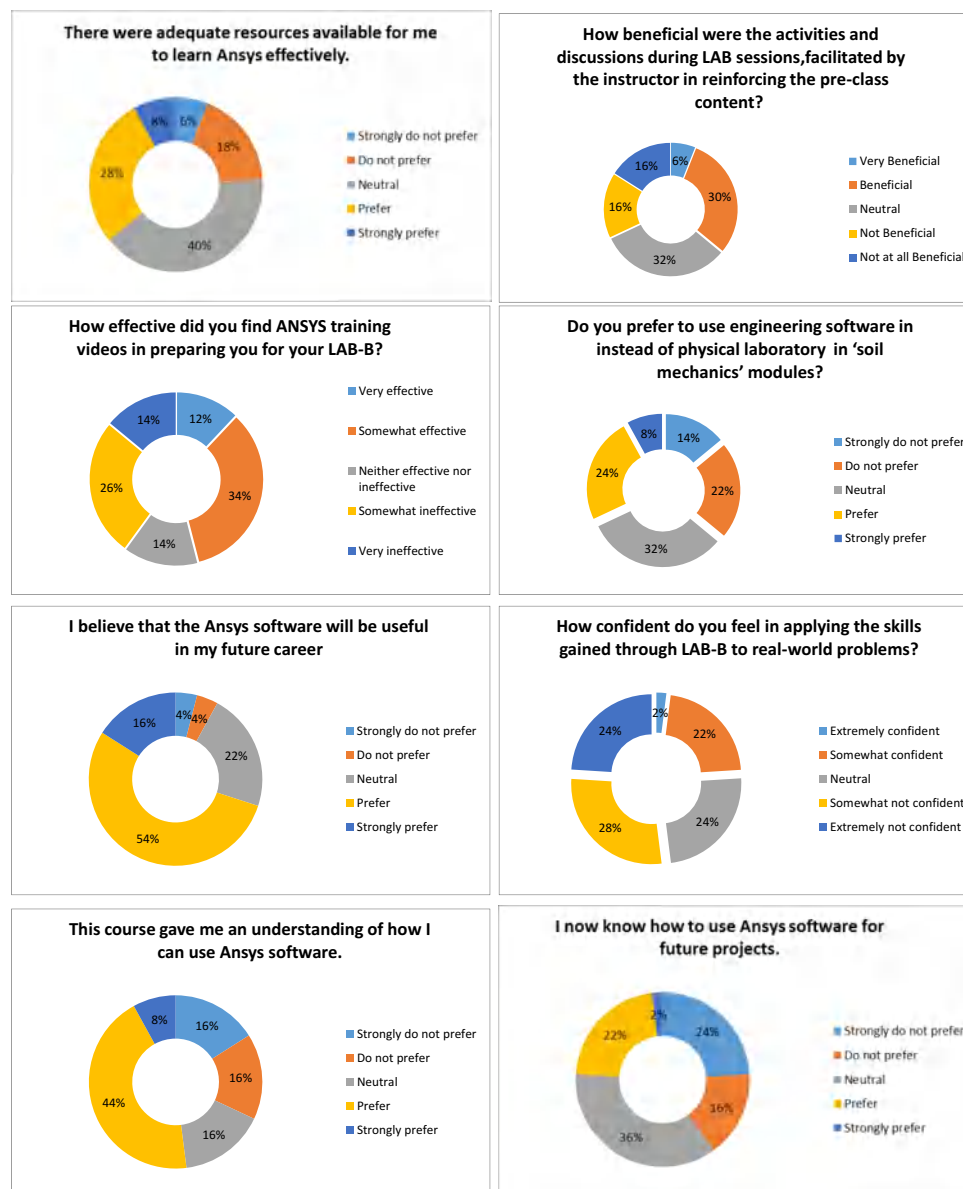
Figure 3. The results of surveys performed by the university in a) academic year 23/24 b) academic year 24/25

To gather student feedback on the revised laboratory sessions, a dedicated survey was also created and distributed to those participating in the upgraded computer laboratory. The survey was made available after the computer laboratory session and encouraged by the instructor during the following lecture. Additionally, dedicated time was allocated within the lecture for students to complete the survey. This took place before the students received their laboratory session and final marks. The survey benefited from a high response rate of 42%, with 78% of participants identifying as male, 18% as female, 2% as non-binary, and 2% as unidentified in terms of gender. The main results of survey have been plotted in Figure 4 and a summary of the survey has been given in Table 2. Also, there were a number of open questions. The Likert scale with the range one to five was used in the survey to find the agreement percentage. Around 58% of students indicated they had received training in other engineering software before using Ansys, with most mentioning (as an explanation question) AutoCAD as the software they had previously worked with, primarily focusing on drawing features. As expected, the majority of students had no prior experience with simulation software. The summary of survey results is provided in Table 2. In terms of available resources, most students found that the combined materials provided by the Strathclyde and Ansys team before the class were very helpful in learning the basics of Ansys tools (see Moghaddasi 2024). However, some students suggested that more experienced laboratory demonstrators should be present during the live classes to assist with troubleshooting. Potential solutions to address these concerns consist in inviting Ansys staff to the live laboratory sessions, organising professional training for the demonstrators, and setting up a troubleshooting forum on the MyPlace page for the class. An interesting piece of feedback from students was that the majority of them expressed a preference for physical laboratories over using engineering software in the Soil Mechanics module. Specifically, it refers to an existing Soil Mechanics laboratory session where students physically measure the hydraulic conductivity of soil. This suggests that while computer-aided laboratory sessions can be valuable, they are not seen as a replacement for hands-on, physical laboratory work, in line with other studies in the literature (Hachich, 2012). Instead, these digital sessions are viewed as complementary, offering a different but useful way to enhance learning, rather than substituting the tangible experience provided by traditional laboratory setups.

There was strong agreement among students that Ansys technology could be beneficial for their future career, although many felt they were not yet competent in using all of its features. A special video was created to demonstrate the capabilities of Ansys Discovery to analyse 3D flow problems. Although the content of this video was not part of the laboratory assessment, many students attempted the instructions and expressed interest in applying the skills learned to real-world challenges, such as multi-stage dewatering techniques, 3D exclusion methodologies for seepage control, and groundwater management for 3D earth dams. Learning these topics typically requires strong visualization and creativity skills, which can be effectively developed through computer-aided simulations. A specific point noted by the instructor was that second-year students lacked sufficient mathematical knowledge to fully understand 2D FEM formulations. As a result, it was decided to introduce the fundamentals of FEM, such as 1D modelling of solid media, as early as the first year of study. This could be incorporated into first-year modules, such as "Engineering Mechanics 1" to establish a foundation for more advanced 2D modelling techniques in the later years.

Table 2. The summary of survey on students' perception for revised computer laboratory

Core areas	Questions	Agreement%
Available resources for Ansys learning	There were adequate resources available for me to learn Ansys effectively.	63%
	How beneficial were the activities and discussions during LAB sessions, facilitated by the instructor in reinforcing the pre-class content?	61%
	How effective did you find Ansys training videos in preparing you for your LAB-B?	59%
	Do you prefer to use engineering software instead of physical laboratory in Soil Mechanics modules?	58%
Ansys for future career	I believe that the Ansys software will be useful in my future career.	75%
	How confident do you feel in applying the skills gained through LAB-B to real-world problems?	70%
	This module gave me an understanding of how I can use Ansys software.	63%
	I now know how to use Ansys software for future projects.	53%

**Figure 4. The detailed results of Survey**

Finally, the results of the assessments for the Soil Mechanics module as a whole were obtained. Figure 5 shows student performance in terms of overall assessments (Figure 5a) and computer laboratory assessments (Figure 5b) across the 2023/24 and 2024/25 academic years. In terms of overall performance, the average marks were similar, with 60% achieved in the 2023/24 academic year and 62% in 2024/25. Notably, there was an increase in the number of high-achieving students in the 2024/25 academic year. In both academic years, computer laboratory assessments received high marks, with scores of 79% in 2023/24 and 69% in 2024/25. There are several reasons for the decrease in students' marks in the revised assessments. In some of the submitted assignments for the 2024/25 academic year, students were unaware that FEM solutions require proper legends, dimensions, and that the results are sensitive to the units of input parameters. In contrast, students in the 2023/24 academic year had better control over the layout of drawings and the units of input parameters when using spreadsheet-based solutions. To mitigate these issues in future delivery, it is recommended that clear guidelines and checklists be provided to students, emphasizing the importance of proper legends, dimensions, and consistent units in FEM solutions. Incorporating practice exercises on unit conversions, along with tutorial sessions and annotated examples, could further support students' understanding. Additionally, peer review, continuous feedback, and targeted software training may enhance students' ability to produce accurate and well-presented results. Additionally, although a free version of Ansys is available to students, most groups opted to use the version installed on the University virtual desktop. As a result, not all students could work with Ansys Discovery simultaneously due to the limited number of licenses available. Introducing basic Ansys features as early as the first year is expected to enhance learning outcomes.

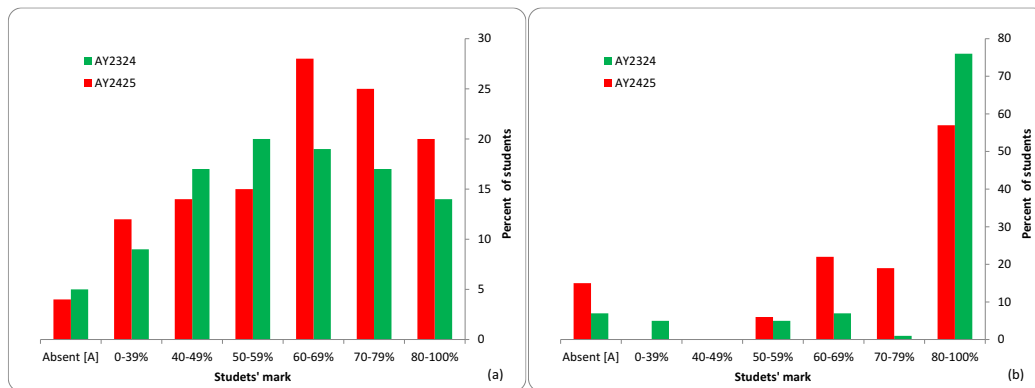


Figure 5. Students' performance across two successive academic years a) overall assessment b) computer laboratory assessments

The authors reflect on their initial experience integrating digital technology into a geotechnical engineering module. Their experience highlights that undergraduate students with limited background in FEM require structured support to grasp the concepts effectively. This can be achieved through clear, simple examples — such as the 1D bar problem — enhanced by strong visual tools provided by user-friendly software. The authors also align with students' feedback that virtual laboratories alone are insufficient to meet all learning objectives and should be complemented with hands-on, physical laboratory sessions.

The ultimate goal of this research is to embed digital technology, particularly computer-aided simulations using Ansys tools, into the existing curriculum of the Civil and Environmental Engineering (CEE) degree program. This will ensure that students develop skills and knowledge that not only align with academic objectives but also have practical industry applications. To achieve this, Ansys technology will be integrated into various CEE classes, enhancing students' learning experiences across multiple years. At the University of Strathclyde, Ansys will be utilized in advanced geotechnical engineering modules in years 3 and 4 (Geotechnical Engineering 1 and 2), as well as in Master's-level modules like Ground Improvement and Reinforcement. The software's capabilities, including elasto-plastic constitutive models such as Mohr-Coulomb, and its robust nonlinear solvers, make Ansys particularly suitable for routine geotechnical simulations. These include key tasks like slope stability analysis and bearing capacity simulations, which are fundamental for real-world geotechnical engineering practice. By incorporating these advanced tools into the curriculum, students will gain the expertise necessary for tackling complex engineering challenges in the industry.

6 Conclusion

This paper has presented a case study of technology-enhanced teaching and learning integrated into the existing curriculum of the 2nd year Soil Mechanics module at the University of Strathclyde. Ansys tools, including Ansys Workbench and Ansys Discovery, were employed in the computer laboratories to assist students in simulating 2D and 3D seepage problems. In the previous academic year (2023/24), the computer laboratories relied on a finite difference method implemented in spreadsheet software. The advantages and disadvantages of the old teaching approach have been discussed based on feedback from both students and instructors. In the updated teaching approach, Ansys tools were incorporated into computer laboratory sessions to challenge students with different 2D water flow problems and familiarize them with digital tools commonly used in industry. With Ansys Discovery, students were able to quickly evaluate the impact of design parameter changes on flow parameters, visualize flow lines and equipotential lines, and estimate total flow at the downstream boundary. The results from two surveys on overall student satisfaction and satisfaction with the computer laboratories were analyzed. The findings revealed a noticeable increase in overall student satisfaction in the current academic year compared to historical data (2023/24), particularly regarding the availability of enhanced learning resources. The survey on the revised computer laboratories also indicated that students recognized the value of learning cutting-edge technologies like Ansys simulations for their future careers, despite working with only limited features of the software. Furthermore, students expressed the importance of preserving physical laboratories alongside the use of simulation-driven technology. Comparing assessment marks across the two academic years, it was observed that students in the revised computer laboratories required additional technical support, such as troubleshooting sessions and earlier exposure to Ansys technology in the first year. To improve the overall student experience throughout the CEE program, there are plans to incorporate Ansys technology into several advanced geotechnical modules in years 3 and 4. This initiative aims to meet the increasing demand for professional geotechnical engineers skilled in numerical modelling and capable of managing complex geotechnical projects.

References

- Airey, D.W., Cafe, P., Drury, H. (2012). The use of online resources to support laboratory classes in soil mechanics. In *Shaking the Foundations of Geo-engineering Education: Proceedings of the International Conference on Geotechnical Engineering Education 2012* (pp. 113-120), Taylor & Francis, London, UK.
- Allawi, F.A. (2011). Educational program for teaching seepage studies (EPTS). *Computer Applications in Engineering Education*, 19(4), pp. 708-716.
- Allawi, F.A. (2023). Educational interactive virtual strain and consolidation tests using LabVIEW and Arduino Uno microcontroller. *Computer Applications in Engineering Education*, 31(5), pp. 1256-1271.
- Hachich, W. (2012). Soil mechanics laboratory classes as an integral part of the learning process. In *Shaking the Foundations of Geo-engineering Education: Proceedings of the International Conference on Geotechnical Engineering Education 2012*, pp. 121-129, Taylor & Francis, London, UK.
- Houston, S.L. (2019). It is time to use unsaturated soil mechanics in routine geotechnical engineering practice. *Journal of Geotechnical and Geoenvironmental Engineering*, 145(5), 02519001.
- Isik, H., Cabalar, A.F. (2018). Sieve analysis and standard penetration test correlations using Microsoft Excel VBA and an iPhone app. *Computer Applications in Engineering Education*, 26(6), pp. 2092-2101.
- Jaksa, M.B. (2020). Reflections on some contemporary aspects of geotechnical engineering education—from critical state to virtual immersion. In *Proceedings of the Online International Conference on Geotechnical Engineering Education 2020 (GEE2020)* (pp. 1-16). International Society for Soil Mechanics and Geotechnical Engineering, London, UK.
- Ledesma Villalba, A., Prat Catalán, P., Lloret Moranco, A., Chacón Flores, R.A., Sondon Sansó, M. (2020). Laboratory experiments in soil mechanics by means of digital twins and low-cost equipment. In *Online Library ISSMG: International Conference on Geotechnical Engineering Education 2020 (GEE2020)* (pp. 1-11). International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE).

Moghaddasi, H. (2024). Utilizing Flipped Classroom Approaches Offered In A Joint Programme: Opportunities And Challenges. Proceedings of the 52nd Annual Conference of SEFI, Lausanne, Switzerland. DOI: 10.5281/zenodo.14256705

Oliver, A. W., Oliphant, J. (1999). A computer-aided learning program for teaching effective stress to undergraduates. *Geotechnical & Geological Engineering*, 17, pp. 85-97.

Pinho-Lopes, M. (2012). Implementation of the use of computing and software in undergraduate Soil Mechanics courses. In *Shaking the Foundations of Geo-engineering Education: Proceedings of the International Conference on Geotechnical Engineering Education 2012*, pp. 193-200, Taylor & Francis, London, UK.

Rehman, Z.U. (2023). Trends and challenges of technology-enhanced learning in geotechnical engineering education. *Sustainability*, 15(10), 7972.

Szavits-Nossan, V. (2012). Learning issues related to basic concepts in geotechnics: A teacher's perspective. In *Shaking the Foundations of Geo-engineering Education: Proceedings of the International Conference on Geotechnical Engineering Education 2012*, pp. 201-208, Taylor & Francis, London, UK.

Toll, D.G., Barr, R.J. (1998). A computer-aided learning system for the design of foundations. *Advances in Engineering Software*, 29(7-9), pp. 637-643.

Wirth, X., Jiang, N.J., Da Silva, T., Vecchia, G.D., Evans, J., Romero, E., Bhatia, S.K. (2017). Undergraduate geotechnical engineering education of the 21st century. *Journal of Professional Issues in Engineering Education and Practice*, 143(3), 02516002.

Yin, Z. Y., Teng, J. C., Wang, H. L., & Jin, Y. F. (2022). A MATLAB-based educational platform for analysis of slope stability. *Computer Applications in Engineering Education*, 30(2), pp. 575-588.

Authors' bios

Hamed Moghaddasi, University of Strathclyde, the UK

Dr. Hamed Moghaddasi (PhD, CEng, MIEAust, MIMMM, FHEA) is a Teaching Fellow in the Department of Civil and Environmental Engineering. He obtained his MSc in Civil Engineering from the University of Tehran in 2013 and completed his PhD in Civil and Environmental Engineering at UNSW, Australia, in 2019. Prior to joining the University of Strathclyde, Dr. Moghaddasi worked as a Postdoctoral Research Associate in Geomechanics at Durham University. His research interests encompass soil-structure interaction, the mechanics of unsaturated soils, computational methods in geomechanics, and smart materials. Passionate about innovative teaching and learning strategies in higher education, Dr. Moghaddasi secured funding from Ansys as a principal investigator to integrate digital technology into the existing curriculum of the Department of Civil and Environmental Engineering. He was also awarded a teaching-research grant from the University of Strathclyde to introduce an AI-enabled computational toolbox into geotechnical engineering education.

Source: Moghaddasi, H. (2024). Utilizing Flipped Classroom Approaches Offered In A Joint Programme: Opportunities And Challenges. Proceedings of the 52nd Annual Conference of SEFI, Lausanne, Switzerland. DOI: 10.5281/zenodo.14256705

Maziar Moradi, University of Strathclyde, the UK

Maziar Moradi is a PhD candidate in the Department of Civil and Environmental Engineering at the University of Strathclyde. With a strong academic background in Rock and Soil Mechanics, he has developed a comprehensive skill set in Geomechanics through his bachelor's and master's studies. During his previous research, Maziar focused on estimating the wear of cutting tools used in tunnel boring machines. This work led to the development of an innovative testing procedure and device, enabling more accurate evaluation of tool wear. His research interests include the application of numerical methods to model complex geotechnical problems. For his PhD, Maziar is investigating the mechanical behavior of bimrocks, combining laboratory experiments with advanced numerical modeling.

Alessandro Tarantino, University of Strathclyde, the UK

Alessandro Tarantino is Professor of Experimental Geomechanics at the University of Strathclyde in Glasgow, Scotland. Current research interests include the monitoring of the soil-plant-atmosphere continuum and the mechanical response of geostructures to climatic loading. He has led major European consortium research projects including the Marie Curie Industry-Academia Partnerships and Pathways 'MAGIC' (Monitoring systems to Assess Geotechnical Infrastructure subjected to Climatic hazards, 2013-2016) and the Marie Curie European Training Network 'TERRE' (Training Engineers and Researchers to Rethink geotechnical Engineering for a low carbon future, 2015-2019). He is editor of the book 'Laboratory and Field Testing of Unsaturated Soils' (2009). He has been keynote/theme lecturer at numerous International Conferences (the 8th International Conference on Unsaturated Soils in 2023 and the ICE Géotechnique Lecture in October 2023 the most recent ones) and has been ranked in the Top 2% most-cited Scientists Worldwide in 2023 & 2024 by Stanford University.

Bridget Ogwezi, Ansys, Inc., Cambridge, the UK

Dr Bridget Ogwezi is a Senior Project Manager on the Ansys Academic team, where she supports engineering education at universities worldwide. She holds a BEng in Civil Engineering from the University of Surrey and an Engineering Doctorate from the Technologies for a Sustainable Built Environment Centre at the University of Reading, completed in collaboration with BuroHappold Engineering. Leveraging her expertise in engineering and sustainability, she works closely with educators to enhance engineering courses and advance innovative teaching practices. In her role at Ansys, she oversees strategic partnerships with academic institutions that align with the company's mission to develop the next generation of engineers. Through these collaborations, she strives to equip students with the skills and tools needed to address real-world engineering challenges.

The role of numerical modelling within a pedagogical framework for soil mechanics courses: implementation for stresses in soils

M. Pinho-Lopes^{1,2} & J. Macedo¹

¹ CERIS and RISCO, Department of Civil Engineering, University of Aveiro, Aveiro, Portugal
mlopes@ua.pt, jmacedo@ua.pt

² School of Engineering, University of Southampton, Southampton, United Kingdom
M.Pinho-Lopes@soton.ac.uk

ABSTRACT: This paper describes the use of numerical modelling in soil mechanics with focus on stress in soils. Over the past 18 years, the authors developed a pedagogical framework for soil mechanics courses, which includes a variety of activities, mostly using active learning. These approaches and how they are interlinked to promote learning on stresses in soils are described. The numerical modelling component is implemented through project-based learning, and engages students in comparative analyses using hand calculations, spreadsheets and numerical models. Students develop their own models and validate them against theoretical solutions. Hand calculations reinforce theoretical principles and analytical skills; spreadsheets offer computational flexibility for parametric analysis. GeoStudio, an advanced numerical tool, enables students to model complex soil conditions beyond manual methods. Benefits of systematically comparing these approaches are highlighted, fostering critical evaluation of advantages and limitations. Feedback sessions help clarify misconceptions and reinforce key concepts. This framework, applied at the University of Aveiro, Portugal, provides a comprehensive experience that scaffolds and promotes autonomy of students when using numerical modelling. The development of deep learning, critical thinking, and digital literacy is promoted and students engage with each other and with teachers in a dynamic, positive learning atmosphere, acknowledging the teachers' commitment to promote effective learning, academic success and preparation for the profession.

Keywords: *Active learning, Finite element method, Spreadsheets, Hand calculations, Critical thinking*

1 Introduction

Over the past 18 years, the authors developed a pedagogical framework for soil mechanics courses, which includes a variety of activities, mostly using active learning approaches. Herein, these teaching and learning activities and how they are interlinked to promote learning on the topic of stresses in soils are described. Particular emphasis is given to the use of numerical modelling to support teaching and learning on this topic. The numerical models were implemented by students during the development of small team projects (project-based learning) and the main goal was to promote deep learning, critical thinking, and digital literacy, while students developed technical skills.

When using numerical modelling to support teaching in soil mechanics there are two possible approaches: 1) to produce educational materials suitable for such courses; 2) ask students to produce their own models. The second approach was adopted, and students were asked to use numerical tools to produce their own models and validate them against calculations obtained using theoretical solutions. These were done both by hand and with spreadsheets. The models were implemented during the development of small team projects using a project-based learning approach. The main educational goal is for students to learn how to implement their own calculations, validate their spreadsheets and carry out a comparative analysis of different results. This paper focuses on the implementation of this pedagogical framework within a soil mechanics course at the University of Aveiro, Portugal.

2 Background

In the 21st century, engineers are facing increasingly complex challenges that require more than just technical expertise. In a world in constant change, engineers need to deal with personal and professional challenges such as climate change mitigation, sustainable management of resources, global health issues like COVID-19 pandemic, natural disasters, risk management, artificial intelligence, digital transformation (Caeiro-Rodríguez et al., 2021; Francis & Norton, 2024). Thus, engineers must possess a set of solid technical knowledge and skills, but also other knowledge, skills and abilities that enable them to address problems in multidisciplinary contexts. According to Borowski (2019), the Partnership for 21st Century Learning (P21) Framework defines three categories of competencies necessary to succeed in the workplace and 21st century society: 1) learning skills, including creativity and innovation, critical thinking and problem-solving, as well as communication and collaboration; 2) literacy skills, encompassing information literacy, media literacy, and ICT literacy; and 3) life skills, which cover flexibility and adaptability, initiative and self-direction, social and intercultural skills, productivity and accountability, along with leadership and responsibility.

Engineering curricula should be designed to prepare engineering graduates with a broad range of technical skills, along with significant generic competencies and soft skills. Critical thinking, deep learning, and digital literacy are key, to adapt to evolving technologies and problem-solving demands.

Critical thinking is a dynamic concept that requires educators to guide students in engaging with both context-specific, empirical knowledge and abstract, reflective knowledge (Ahern et al., 2012). Critical thinking is a reflective cognitive skill that involves analysing, evaluating, and synthesising relevant information to construct an argument and make informed decisions (Ennis, 1993; Ghanizadeh, 2017; Putra et al., 2021). It is a fundamental skill in engineering, as it enables engineers to analyse problems systematically, evaluate multiple solutions, and make informed decisions, essential for designing safe, efficient, and sustainable systems (Ralston & Bays, 2013; Kenyon, 2016; Milovanovic et al., 2021). Exposing engineering students to a variety of approaches allows developing the ability to use knowledge and facts to create ideas, concepts and solve problems, and apply them in real world / realistic contexts.

Also crucial in an era of constant and accelerated social, economic and technological change is deep learning, since professionals must continuously learn and innovate to address increasingly complex challenges. Deep learning is generally defined as an approach to understanding content by connecting prior knowledge with new concepts, linking theoretical ideas to real-world applications, organizing and structuring information into a coherent framework, and critically assessing knowledge (Karkoub et al., 2020). Deep learning goes beyond memorization of facts and information, it promotes a profound understanding of fundamental principles that allows engineers to apply their knowledge creatively in various contexts and novel situations, characteristic of real world (Qadir et al., 2020).

Nowadays, digital literacy skills are also critical for modern engineering professionals, since most daily tasks are supported by advanced computational tools, simulations, artificial intelligence and data-based decision-making. Engineers must understand how to use these technologies and to critically assess their accuracy, limitations, and ethical implications (Mökander et al., 2021; Hariri, 2023). For that, engineering students (and educators) need to develop a wide range of cognitive, social and emotional competencies, such as collaboration, communication, creativity, information literacy, socio-emotional skills (Silber-Varod et al., 2019). These competencies make up digital literacy, which is essential for training, learning, upskilling and reskilling with digital technologies in today's virtual education environments (Caratozzolo et al., 2021) and for the future professional life of engineering graduates.

Current civil engineering curricula demand the integration and development of all these skills to ensure that 21st-century engineers are well prepared to tackle global challenges, from climate change mitigation to resilient infrastructure development, while adapting to the constantly evolving fields of engineering and technology. For that, it is fundamental a shift from traditional, lecture-based teaching to more dynamic, skills-oriented education based on active learning strategies. Therefore, different strategies can be used to engage students in real/realistic problem-solving, such as project-based learning (PjBL), problem-based learning (PBL), team-based learning (TBL), challenge-based learning (CBL), hands-on and experiential learning (EL) and flipped classrooms (FC). Current challenges also require that engineering graduates are adaptable, innovative, and proficient in advanced technologies. Hands-on experiences with digital tools like numerical modelling software, Building Information Modelling (BIM), and Geographic Information Systems (GIS), are essential to enhance technical competencies. Many of these strategies foster teamwork and communication skills, crucial for addressing complex engineering

problems. Encouraging critical thinking and ethical decision-making helps students evaluate multiple solutions while considering environmental, economic, and social impacts. By integrating these strategies in courses, civil engineering education can move beyond theory, ensuring that students develop knowledge, skills, and mindset necessary to their professional life.

In the specific case of geotechnical engineering education, the use of numerical modelling tools has become increasingly present, even in introductory courses. Geotechnical engineering deals with highly complex problems that demand a solid understanding of theoretical concepts to ensure the successful execution of high-quality engineering projects (Schweiger et al., 2019; Lemos et al., 2024). The benefits of numerical analysis in solving practical problems are well recognized, and advancements in software and hardware have made their application in practice more feasible with reasonable effort (Schweiger et al., 2019). But for this, it is fundamental that students understand the potential and risks involved in using these tools. Shiau et al. (2016) highlight the importance of integrating physical models with numerical analysis while teaching advanced geotechnical concepts, suggesting that this combination promotes engagement and deeper understanding among students. Lemos et al. (2024) conclude that the integration of software and digital tools is a highly effective pedagogical strategy, enhancing the teaching-learning process by fostering active engagement, interactive learning, and a deeper comprehension of theoretical principles and practical applications. In their study, Lemos et al. (2024) combined different digital tools (including numerical) that students used to generate, analyse, and interpret results for different laboratory tests, carry out slope stability analyses, rock masses characterization and analyses, and flow studies.

In most cases, the use of numerical modelling is promoted mostly at postgraduate level. However, according to the literature this could also be done at undergraduate level (Gallardo-Pastor et al., 2021).

This study describes the use of numerical modelling to support teaching and learning in an introductory course on soil mechanics, specifically to the analysis of the stress state in soils, in order to promote deep learning, critical thinking and digital literacy among undergraduate students. Students were asked to use numerical tools to produce their own models and validate them against calculations made using theoretical solutions done by hand and with spreadsheets.

3 Case study

3.1 Soil Mechanics I course

The case study described herein refers to an undergraduate course on soil mechanics within the bachelor's degree in civil engineering at University of Aveiro (UA), Portugal. This study programme has two consecutive courses on soil mechanics, Soil Mechanics I and Soil Mechanics II. By integrating theoretical concepts with practical applications, both courses on soil mechanics aim to provide students with a comprehensive learning experience, to prepare them for the complexities of geotechnical engineering practice. Herein an example referring to the Soil Mechanics I course is included.

The Soil Mechanics I (SMI) course is part of the third year of the bachelor programme (total of 180 ECTS, European Credit Transfer System). SMI has 6 ECTS and the contact time is composed by a theoretical-practical (TP) class with 2 hours per week, a practical (P) class with the same number of hours per week and a tutorial class with the duration of 1 hour per week, usually over 14 weeks. At UA, each ECTS corresponds to 27 hours of student workload and includes class time, preparing assessments, independent study, research, teamwork, and report writing.

In SMI some soil mechanics fundamental concepts and principles, essential for civil engineering design, are presented. The syllabus includes: 1) Physical properties and soil classification – Understanding sedimentary and residual soils; 2) Stress state in soils – Evaluating stress distribution, including capillarity effects; Mohr-Coulomb failure envelope; 3) Water in soils and seepage – Analysing water flow through soil; 4) Compressibility and consolidation – Studying settlement behaviour of clay soils. Although the case of unsaturated soils is described, the course deals mostly with fully dry or fully saturated soils.

The course syllabus follows closely Fernandes (2017), namely chapters 1 to 4. Students are encouraged to get a copy of the book, use it as study material and to create their personal library. The book is written in Portuguese and is comprehensive, in a way the authors feel is useful for students. Over the years, the authors produced additional resources that are available to students in a range of formats. A workbook with a selection of exercises is made available to students and is solved in and out of class.

Over the years, the number of students on SMI has varied, reflecting the number of students enrolled in Civil Engineering. In Portugal, in 2012 to 2014 there was a significant drop in applications to across all universities. This has been changing; recently, the number of students at UA ranges from 25 to 30.

3.2 Teaching and learning strategies

The authors started teaching this course in 2007/2008. Before that, traditional teaching methods were used, with expositive lectures and moments for solving exercises using hand calculations. Since 2007/2008, the authors have been introducing innovative practices to promote active learning.

The first and the most disruptive transformation involved the implementation of a project-based learning (PjBL) model, incorporating both cooperative learning (jigsaw method) and collaborative learning approaches (Pinho-Lopes et al., 2011; Pinho-Lopes & Macedo, 2016). Students tackle projects, as a small team (up to 4 students), that involve carrying out laboratory tests or using numerical tools (depending on the topic) and using spreadsheets to perform calculations. Students are encouraged to work in teams on realistic geotechnical problems, while developing technical expertise and transferable skills, such as: numerical modelling proficiency for solving typical soil mechanics problems, teamwork and collaboration through cooperative/collaborative learning, effective communication (oral and written).

From 2015/2016 onward, guided exercises were introduced (Oliveira et al., 2018; Macedo et al., 2020; Macedo & Oliveira, 2024). Using the learning management system (LMS), students are challenged to solve complex problems using a step-by-step process, helping them link models and concepts. Guided exercises are set up in the LMS and include immediate feedback on students' answers.

In 2019/2020, immediate feedback sessions were introduced to implement assessment for, of, and as learning (as described by Pinho-Lopes & Powrie, 2020). In 2020/2021, flipped learning was implemented in a hybrid model, in response to the COVID-19 pandemic (Pinho-Lopes & Macedo, 2022). This approach was abandoned; however, videos produced then are made available to students and are additional learning resources. In 2022/2023, a new approach was introduced, combining hands-on learning with team-based learning to promote learning of fundamental, key concepts within soil mechanics (Macedo & Pinho-Lopes, 2023; 2024). Additional sessions, with only hands-on activities or TBL have been introduced since.

In this paper the focus is the use of numerical modelling tools namely for analysing stresses in soils. The different teaching and learning strategies that prepare students and lead them to the development of the small team projects in that context is described in detail in the following section.

4 Pedagogical framework: stresses in soils

4.1 Introduction

The following subsections describe the pedagogical framework adopted in SMI for the topic of stresses in soils. These have been built incrementally, since 2007/2008, to promote active learning and address limitations identified during that process. Herein, these strategies and activities have been grouped as: formal teaching; hands-on and TBL sessions, independent study, and project-based learning. Illustrative examples of the educational material used are included; their use should be considered within the context of the SMI course (1st cycle degree and an introductory course on soil mechanics) and the students that enrol in the Civil Engineering degree in Portugal, particularly at University of Aveiro.

4.2 Formal teaching

In formal teaching, there are two types of contact time. In theoretical-practical (TP) classes, mostly a traditional model is used, combining content exposition with solving simple exercises. The teachers present the principles and concepts associated with stresses in soils, for both the at-rest condition and after induced changes near the ground surface; then, simple exercises are solved in-class to reinforce understanding. These classes are characterized by knowledge transmission, which includes learning through listening and copying, note-taking, and active learning tasks. The latter include questioning, discussion, and problem-solving. In practical (P) classes, students apply theoretical knowledge and skills acquired during TP classes to solve more complex exercises, which require deeper, analytical and

more advanced problem-solving skills. Increasing the complexity of exercises aims to develop students' ability to apply theoretical principles and concepts to new scenarios, critically analyse different conditions, and work independently or with others to find solutions.

Stresses in soils result from loads applied on their boundaries or within the soil mass (including the self-weight of soil). Applied loads can be point, line or distributed loads, and resulting stresses decrease in magnitude with distance from the applied loads (Salgado, 2022). In SMI, solutions from elasticity theory are used to calculate stress components for two- or three- dimensional problems at a point within a soil mass. Elasticity solutions are applicable if the deformations within the soil mass are small enough, i.e., the soil is far from collapse or sliding. These solutions simplify the soil response, assuming a semi-infinite, homogeneous, isotropic, linear and elastic material. Figure 1 illustrates some of these solutions.

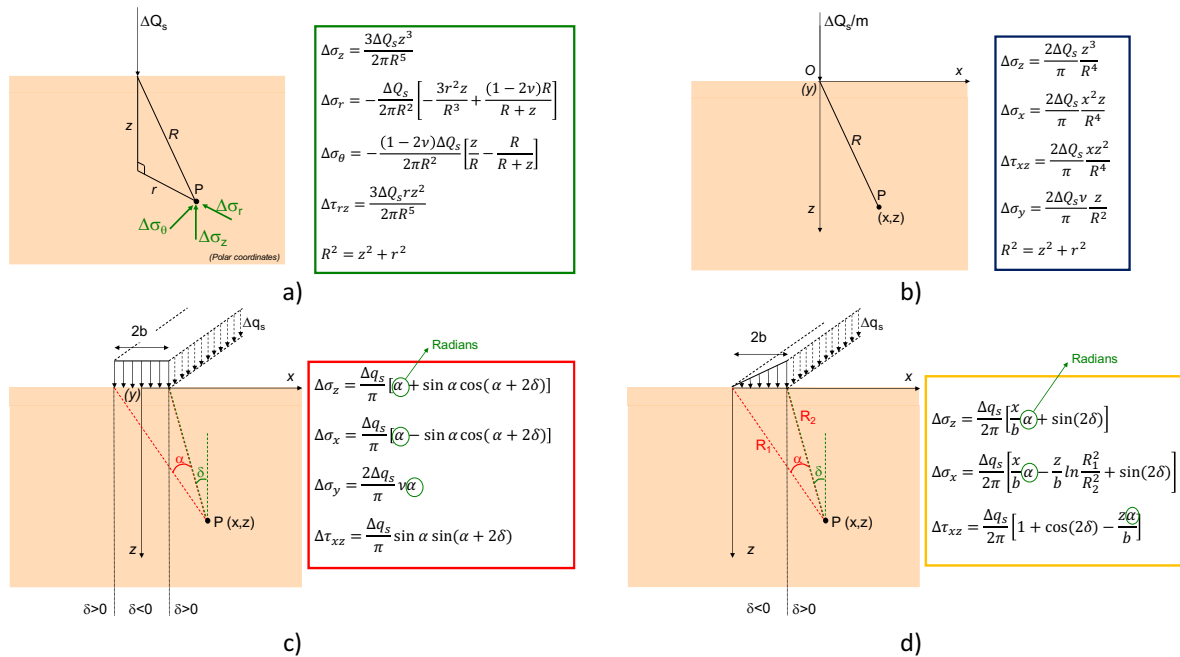


Figure 1. Solutions from elasticity theory for surface loading: a) point load; b) line load; infinite strip loaded by c) uniform vertical stress; d) triangular vertical stress (adapted from Fernandes, 2017)

Simple illustrative problems are analysed and solved in TP classes, while more complex exercises are solved in P classes. These include layered soil profiles and combination of load types, requiring application and integration of concepts and knowledge. In a typical application exercise solved in P classes (Figure 2) students are guided into using solutions from elasticity theory to calculate stress increments due to a combination of surface loads on a particular point within the soil mass; then, they complete the exercise for additional points. Other exercises combine the calculation of the initial (at rest) stress state, stress increments and resulting stress state. Basic concepts on the shear strength of soils and the Mohr-Coulomb failure criteria are introduced. This is then used to assess if the stress for given points within the soil mass reaches failure. Graphical representation of stresses and their changes due to surface loading are covered and students plot stress paths, Mohr circles and the soil failure envelop.

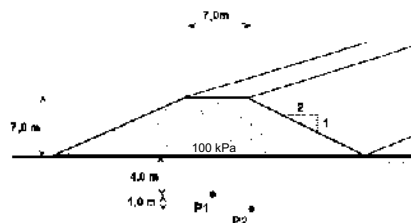
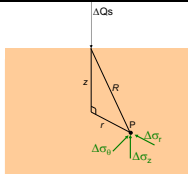
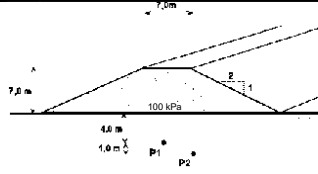


Figure 2. Example of a realistic problem used to practice the application of elasticity theory solutions to calculate stress increments due to a combination of surface loads (from the workbook and for P classes)

Thus, formal teaching sessions are organised to tackle concepts and their application in a progressive, cumulative way, starting with simple illustrative exercises and advancing to more complex and realistic

cases, linking theory and textbook exercises with real geotechnical applications, often illustrated with photos and videos (Table 1).

Table 1. Examples of progressive exercises used to link theory and textbook exercises with real geotechnical applications for stresses in soils

	TP classes	P classes
Elastic theory solutions	Point load Line load	Strip load: uniform and triangular Uniform load: circular and rectangular area Combinations
Example of problems worked in class		
Real-life cases represented	Electric power line pole Pipelines	Retaining wall foundation Highway embankment Storage tank or silo Mat or raft foundation

4.3 Hands-on and team-based learning sessions

The concept of effective stress was introduced by Terzaghi to represent the fraction of total stress that is carried at the particle contacts within a saturated soil. According to the effective stress principle, the total force acting on an area of soil is supported by the soil skeleton (via soil particles contacts) and by the pore fluid. Often, students struggle to understand the concept of effective stress and its relevance within soil mechanics. To promote learning of fundamental concepts within soil mechanics, the authors designed a pedagogical approach that combines hands-on learning and team-based learning (TBL) (Macedo & Pinho-Lopes, 2024). First, students form small groups and carry out a simple experiment, designed to enable visualisation and demonstration of the fundamental principle or concept covered. This is followed by a TBL session that starts with an individual quiz. Then, students get back together in the same small groups and tackle the quiz as a team. Finally, there is a large group discussion, where answers to the quiz are analysed and discussed, underlying contents and theories are systematised and linked. Further details can be found in Macedo & Pinho-Lopes (2024).

For the stresses in soils, the illustrative hands-on experiment was adapted from Elton (2001) Bucket of Bolts Experiment. This involves filling a container with loose aggregate and positioning bolts with tightened nuts and washers at its bottom and top. When the container is upturned, the aggregate remains within it, demonstrating how increasing forces at particle contacts drastically changes the behaviour of soil, thus highlighting the concept of effective stress and its role on the soil shear strength.

4.4 Independent study

As with any course, independent study is pivotal in deepening students' understanding. To direct independent study and promote self-directed learning, critical thinking, and problem-solving skills, the authors designed and implemented a structured set of pedagogical resources, which allows students to engage with content at their own pace, while reinforcing theoretical and practical knowledge.

The core textbook adopted (Fernandes, 2017) is an overarching resource that covers the full syllabus. Chapter 2 is dedicated to the stresses in soils.

This is complemented with a set of recorded lessons implemented on the LMS and prepared during the COVID-19 pandemic for a flipped classroom strategy (Pinho-Lopes & Macedo, 2022). Each lesson consists of a short video, a simple problem/question about the content covered and a summary. The lessons span the full syllabus and provide flexibility, as students can review key concepts as needed and revisit complex topics for clarification. Seven lessons are available on stresses in soils and cover: 1) Stresses in soils and principle of effective stresses; 2) At-rest stress state; 3) Stresses induced by external loads - introduction and formulation; 4) Elasticity theory and its solutions applicable to soil

mechanics; 5) Shear failure in soils – Mohr-Coulomb failure criteria; 6) Failure criteria on a s, s', t space (2D stress invariants) and local versus global failure; 7) Capillarity in soils.

A dedicated workbook has been prepared and includes nine structured problems on stresses in soils, which range from basic applications to more advanced, complex and realistic problems. The workbook is updated regularly and spreadsheets with base data are made available to students for use in class.

Via LMS (Moodle), guided exercises are available. The objective is to promote knowledge application and analytical reasoning in problem-solving by integrating conceptual questions with quantitative calculations. Typically, a guided exercise is developed based on an end-of-chapter or exam problem (more complex and requiring several types of calculations). While solving exercises in a structured way, students apply and integrate theoretical concepts and analytical reasoning using a step-by-step process. This incorporates automatic feedback that includes: 1) whether the answer to each question is correct; 2) possible reasons for an incorrect answer, without revealing its solution. Some information on relevant parts of the textbook or lessons are included. For stresses in soils, there is one guided exercise, divided into two parts on: 1) soil properties relevant for the subsequent stress analysis; 2) stress state at-rest and after construction of a structure and its analysis and graphical representation on an s, s', t space.

The resources available for independent study and how they are linked to in-class structured activities foster engagement and self-regulation, allowing students to take responsibility for their learning process. By integrating various and diverse learning resources, students can have a comprehensive and flexible learning experience tailored to their own needs.

4.5 Project-based learning

The project-based learning (PjBL) approach adopted occurs mostly outside class time and includes mandatory team projects designed to enhance collaborative learning, discussion sessions to give individualised feedback to each team, and individual grading of team projects through peer assessment. The projects are summative, aligning with an assessment for learning approach rather than a traditional assessment of learning, as recommended by Larkin & Richardson (2013). These projects are open-ended, designed around realistic geotechnical case studies adapted to the students' knowledge level. The primary objective when introducing this approach was to promote critical thinking and engineering judgment, alongside strengthening theoretical understanding and practical problem-solving skills.

On stresses in soils, a typical team project (example in Figure 2) includes calculations of initial stress state for a simplified soil profile, and new stress states after construction of a given (simple) structure, using elastic solutions and assuming fully drained conditions (SMI is an introductory course). Students generate information using different approaches: hand calculations, spreadsheets and numerical models. The main educational goal is for students to learn how to implement their own calculations and carry out a comparative analysis of different results. Often these spreadsheets are increments on the ones created by students in class (P), while solving exercises to perform calculations and to compare results with those obtained through hand calculations. With the introduction of numerical tools, students can model realistic soil conditions and stress distribution scenarios not easily replicable manually.

Most students have no contact with numerical models before the SMI course. This creates additional challenges that need addressing. The chosen software, GeoStudio, is user-friendly and is organised in modules that can be combined to create complex analysis. The module used is Sigma, with the finite element method. In-class, the authors present the software and its main features, illustrating how to create and edit simple models. A range of additional resources is made available to students, including recorded tutorials (produced by the authors) and links to illustrative examples and tutorial videos. Then, students are challenged to prepare their own models.

Even if students lack theoretical knowledge on the finite element method, during the tutorial session key aspects of numerical modelling are discussed: 1) soil mass to include; 2) boundary conditions and their meaning; 3) material models and properties; 4) mesh requirements (only the element size can be changed); 5) types of outputs and how they compare with those generated manually or using spreadsheets. The teacher shows how to generate a model, discussing aspects relative to geometry, materials, boundary conditions, and meshing, and promotes discussion on their influence on results. The actual results and how automatic generated outputs can be used for data analysis are included.

Figure shows how the problem in Figure can be tackled by students: Figure a refers to a model idealisation, to simplify the analysis; Figure b, c and d include outputs generated by students.

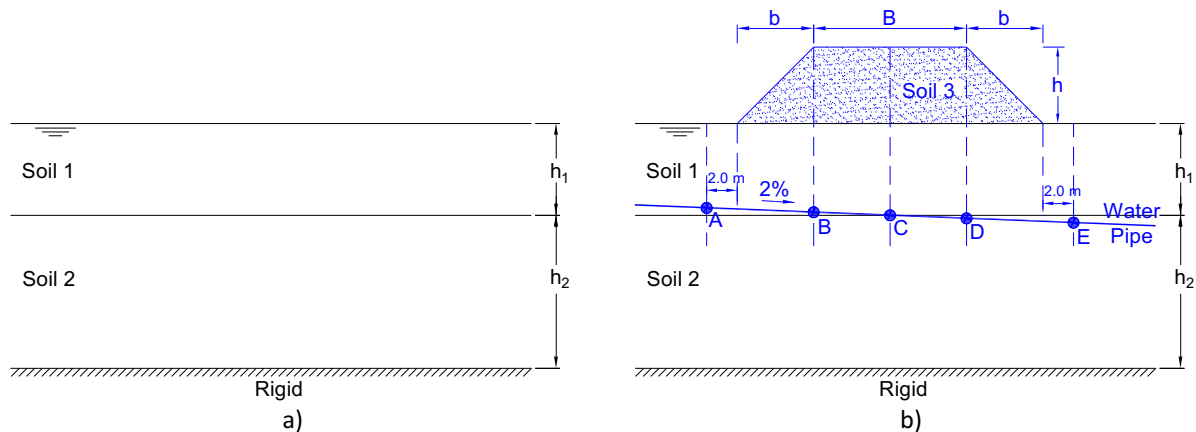


Figure 3. Example of a stress state problem: a) soil profile; b) soil profile with the structure (embankment) and a water pipe with a 2% slope (blue line) where points A to E are located

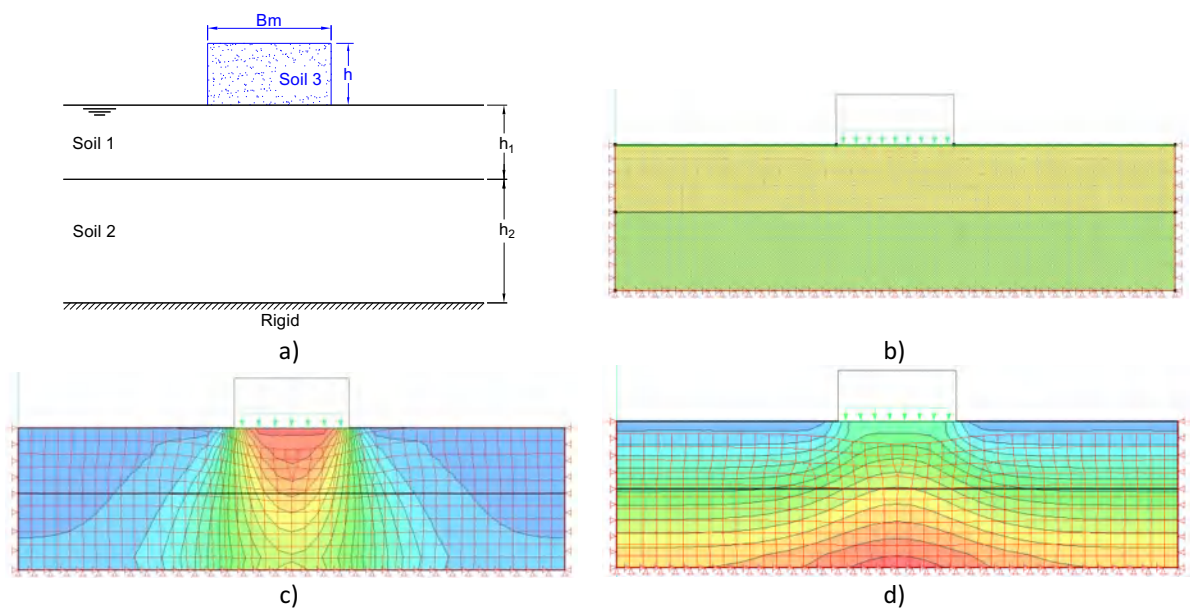


Figure 4. Example of a model developed by a group of students in GeoStudio: a) simplified problem (groups choose the distance Bm); b) model definition; c) results - bulbs of pressure (lines or contours of equal stress increase); d) results – total vertical stress

The project-brief specifies the need to compare results obtained using different tools: hand calculations, spreadsheets and numerical models, including the type of outputs to be compared. Mohr's circles of stress and variation of stresses along a given section are included. Figure shows an example of data from the numerical models of a group of students.

Students prepare a report that summarises the results generated, compare data obtained using different tools and discuss them; they also submit their spreadsheets and GeoStudio files. Then, students receive feedback during discussion sessions. Each discussion session lasts around 45 minutes per team. This allows teachers to give specific feedback to each team, clarifying misconceptions, correcting errors and promoting critical comparison of results. For example, the group GeoStudio files are used to illustrate the influence of certain changes on the output generated and improve correspondence between results obtained using the different tools. Often, a document with general feedback is made available to students, including information on aspects relevant for future work and reports.

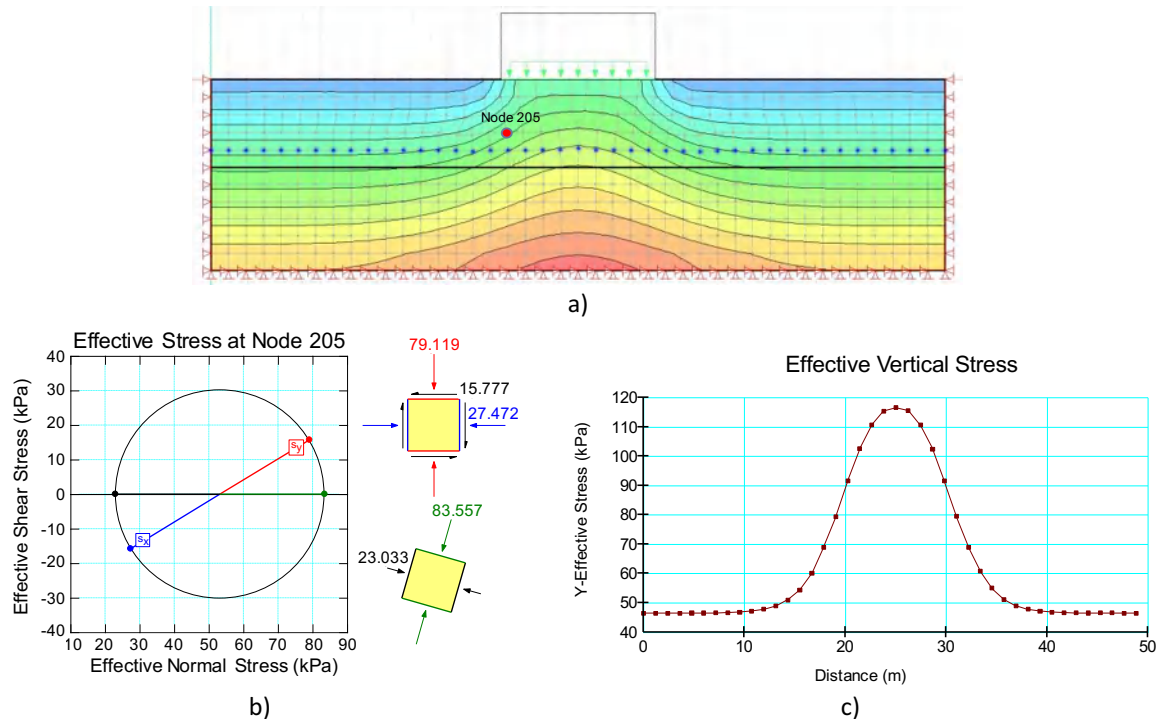


Figure 5. Example of analyses done by students based on the numerical model: a) overview of model and total vertical stresses; b) Mohr circle with effective stresses at node 205; c) effective vertical stresses along a horizontal section - blue dots in a)

4.6 Overview of the framework and its implementation for the stress state of soils

The pedagogical framework developed includes a variety of teaching and learning strategies and resources that have been systematically designed, developed and implemented to facilitate an integrated, and adaptable learning experience. The main aim is to foster personalized learning process, tailored to individual student needs. Table 2 maps the different strategies and resources to address the syllabus on the topic of stresses in soils.

Table 2. Mapping of the pedagogical framework developed for the topic of stresses in soils

Syllabus: stresses in soils	In-class activities				Out-of-class activities		
	Formal teaching		Hands-on learning	Team-based learning	Independent study		Project-based learning
	TP	P			Textbook and lessons	Guided exercises	
Concept of stress in soil mechanics	✓	✓	✓	✓	✓	✓	✓
Principle of effective stress	✓	✓	✓	✓	✓	✓	✓
At-rest stress state	✓	✓		✓	✓	✓	✓
Capillarity effects	✓	✓	✓		✓	✓	✓
Stresses induced by external forces. Stress increments using elastic solutions	✓	✓			✓	✓	✓
Combination of at-rest and incremental stress states	✓	✓			✓	✓	✓
Mohr-Coulomb failure envelope. Local failure	✓	✓			✓		✓

Within this framework, project-based learning is an integrating element which links different learning activities, content and skills into a cohesive, comprehensive and meaningful learning experience,

centred around a realistic case study. Numerical modelling plays an important role, as it requires the application of the knowledge and skills for project development. First, students need to become familiar with the tool, developing the relevant models and understanding how specific aspects modify results. Second, students solve the problem and carry out analysis mimicking work within a professional context.

4.7 Discussion

To understand the students' perspective and ensure continuous improvement of the pedagogical framework, their feedback has been collected systematically. Four types of data have been used: 1) marks and academic success; 2) students' perceptions from informal discussions (in and out of class), and programme committee meetings; 3) short surveys prepared by the teachers; 4) institutional surveys (Teaching Quality Assurance System). This focuses mostly on the whole course, with no specific data on the topic of stresses in soils, but some relevant data can be found in Macedo & Pinho Lopes (2018).

This framework has been built progressively over the last 18 years. Thus, data on students' performance cannot be directly compared to performance using a traditional approach. The framework does not always have a direct improvement on marks. However, since 2019, the number of students enrolled that engage and succeed in the course (59% to 85%) and that submit assessment and are approved (71% to 94%) indicates that there is a positive effect on academic success.

Overall, students acknowledge and appreciate the variety of resources and strategies associated with the pedagogical framework in place. They describe a dynamic and positive learning atmosphere and the commitment of the teachers in their learning, academic success and preparation for the profession.

A significant part of learning process occurs during the feedback sessions, as several misconceptions are deconstructed. Typical misconceptions are varied and depend on the students, their experience and even their personality. Using their spreadsheets and their GeoStudio files to check formulas and illustrate how changing certain modelling parameters influences the results is powerful.

Numerical models can be used successfully by undergraduate students within soil mechanics courses, if instructors scaffold students in that process and promote progressive independence and autonomy. While developing numerical models, students face several challenges, related to software proficiency, selection of appropriate input parameters, mesh generation, definition of boundary and loading conditions, validation and interpretation of results, computational limitations. These are addressed in different ways and to different degrees. The pedagogical framework developed promotes progression and increasing confidence and autonomy, so students engaging with the course will become more comfortable with the tools used. Tutorial sessions on the software address some of these aspects, but only when creating their models will students start to understand their importance. Thus, students need to develop a strong theoretical foundation and improve their software proficiency through practice and tutorials, so they can select adequate input parameters based on soil properties, literature and real conditions. They also need to have some understanding on how the mesh generation and boundary and loading conditions influence the model outputs. Calibration and validation exercises of numerical models are essential to ensure adequate idealisations. Critical comparison of results obtained using different tools, namely hand calculations and spreadsheets, helps promote such an approach to numerical modelling. Teachers feedback moments are pivotal to obtain guidance, clarify misconceptions, refine models, identify benefits and limitations inherent to the use of numerical modelling and compare results obtained by different methods.

5 Concluding remarks

The use of numerical tools within the context of an undergraduate course on soil mechanics was presented. For the past 18 years, the authors have been developing a pedagogical framework that promotes active and personalised learning experiences, while fostering the development technical and soft skills. The framework was mapped with illustrative examples for the topic on stresses in soils.

Often, the use of numerical models in geotechnical education is promoted at postgraduate level. The authors believe that this can be done successfully at undergraduate level, provided that students are adequately supported. This framework, applied at the University of Aveiro, Portugal, provides a comprehensive experience that scaffolds and promotes autonomy of students when using numerical modelling. The development of deep learning, critical thinking, and digital literacy are promoted, and

students engage with each other and with the teachers in a dynamic and positive learning atmosphere, acknowledging the teachers' commitment to promote effective learning, academic success and preparation for the profession.

Acknowledgments

This work was supported by FCT – Fundação para a Ciência e Tecnologia, I.P. by project reference UIDB/04450/2020, DOI identifier 10.54499/UIDB/04450/2020 and by the project UIDB/04625/2025 of the research unit CERIS.

References

- Ahern, A., O'Connor, T., McRuairc, G., McNamara, M., O'Donnell, D. (2012). Critical thinking in the university curriculum—the impact on engineering education. *European Journal of Engineering Education*, 37(2), pp. 125-132.
- Borrowski, T. (2019). The battle for kids p21 framework for 21st century learning. University of Illinois at Chicago.
- Caeiro-Rodríguez, M., Manso-Vázquez, M., Mikic-Fonte, F. A., Llamas-Nistal, M., Fernández-Iglesias, M. J., Tsalapatas, H., Heidmann, O., De Carvalho, C. V., Jesmin, T., Terasmaa, J., Sørensen, L. T. (2021). Teaching soft skills in engineering education: An European perspective. *IEEE Access*, 9, pp. 29222-29242.
- Caratozzolo, P., Alvarez-Delgado, A., Sirkis, G. (2021). Fostering digital literacy through active learning in engineering education. In 2021 IEEE Frontiers in Education Conference (FIE) (pp. 1-6). IEEE.
- Elton, D. J. (2001). *Soils magic*. American Society of Civil Engineers, Reston, Virginia, United States of America.
- Ennis, R. H. (1993). Critical thinking assessment. *Theory into Practice*, 32(3), pp. 179–186.
- Fernandes, M. M. (2017). *Mecânica dos Solos*. Vol. 1: Conceitos e princípios fundamentais. 5th Edition, extended to unsaturated soils. U.Porto Editorial, Porto, Portugal.
- Francis, N., Norton, E. (2024) Educating civil engineers for the twenty-first century: the new-model engineer. *Proceedings of the Institution of Civil Engineers - Civil Engineering*, 177 (2). pp. 63-71.
- Gallardo-Pastor, L. Y., Yacila, J., Poémape, A. (2021). Perception of the undergraduate student about utility of numerical modelling techniques as a didactic resource for scientific research in Civil Engineering. In 2021 International Symposium on Accreditation of Engineering and Computing Education (ICACIT) (pp. 1-5). IEEE.
- Ghanizadeh, A. (2017). The interplay between reflective thinking, critical thinking, self-monitoring, and academic achievement in higher education. *Higher Education*, 74(1), pp. 101–114.
- Hariri, W. (2023). Unlocking the potential of ChatGPT: A comprehensive exploration of its applications, advantages, limitations, and future directions in natural language processing. *arXiv preprint arXiv:2304.02017*.
- Karkoub, M., Yang, C. L., Karkoub, W., Raslan, M. (2020). Undergraduate cross-class research projects for deep learning in engineering education. *Advances in Engineering Education*, 8(2), n2.
- Kenyon, T. (2016). Critical thinking for engineers and engineering critical thinking. In 2016 2nd International Conference of the Portuguese Society for Engineering Education (CISPEE) (pp. 1-4). IEEE.
- Larkin, H., Richardson, B. (2013). Creating high challenge/high support academic environments through constructive alignment: student outcomes. *Teaching in higher education*, 18(2), pp. 192-204.
- Lemos, C. C. D. S., Dias, L. O. F., Barbosa, P. S. D. A., Marques, E. A. G., Ferraz, R. L., Nalon, G. H. (2024). Digital tools used on the teaching-learning process in geotechnical engineering. *Soils and Rocks*, 47(2), e2024004923.
- Macedo, J., Oliveira, P. C. (2024). Use of ICT to implement an active learning strategy in soil mechanics courses at undergraduate level. *Soils and Rocks*, 47(2), e2024007323.

- Macedo, J., Pinho-Lopes, M. (2018). Using Different and Complementary Teaching Tools in Project-Based Learning Application to Civil Engineering - courses on Soil Mechanics. In 018 3rd International Conference of the Portuguese Society for Engineering Education (CISPEE), 6p. <https://doi.org/10.1109/CISPEE.2018.8593494>
- Macedo, J., Pinho-Lopes, M. (2023). Blending Hands-on Learning and Team-based Learning in Soil Mechanics: Phase Relationships for Soils. In 2023 5th International Conference of the Portuguese Society for Engineering Education: CISPEE, 7p. <https://doi.org/10.1109/cispee58593.2023.10227626>
- Macedo, J., Pinho-Lopes, M. (2024). Key concepts in soil mechanics: simple hands-on and team-based strategies to promote active learning. In *Geotechnical Engineering Challenges to Meet Current and Emerging Needs of Society* (pp. 641-646). CRC Press.
- Macedo, J., Pinho-Lopes, M., Oliveira, C.G., Oliveira, P.C. (2020). Two complementary active learning strategies in soil mechanics courses: Students' perspectives. In 2020 IEEE Global Engineering Education Conference: EDUCON. pp.1696-1702 <https://doi.org/10.1109/EDUCON45650.2020.9125334>
- Milovanovic, J., Shealy, T., Katz, A. (2021). Higher perceived design thinking traits and active learning in design courses motivate engineering students to tackle energy sustainability in their careers. *Sustainability*, 13(22), 12570.
- Mökander, J., Morley, J., Taddeo, M., Floridi, L. (2021). Ethics-based auditing of automated decision-making systems: Nature, scope, and limitations. *Science and Engineering Ethics*, 27(4), 44.
- Oliveira, C.G., Macedo, J., Oliveira, P.C. (2018). Promoting understanding and academic success using Guided Exercises supported by ICT. In 2018 3rd International Conference of the Portuguese Society for Engineering Education: CISPEE, 6p <https://doi.org/10.1109/CISPEE.2018.8593466>
- Pinho-Lopes, M., Macedo, J., Bonito, F. (2011). Cooperative learning in a Soil Mechanics course at undergraduate level. *European Journal of Engineering Education*, 36(2), pp. 119-135.
- Pinho-Lopes, M., & Macedo, J. (2016). Project-based learning in Geotechnics: cooperative versus collaborative teamwork. *European Journal of Engineering Education*, 41(1), pp. 70-90.
- Pinho-Lopes, M., Macedo, J. (2022). Mecânica dos Solos – implementação de flipped learning em ensino híbrido. In *CNaPPES21 - 7.º Congresso Nacional de Práticas Pedagógicas no Ensino Superior*, 12 a 16 julho 2021, Livro de Atas, pp. 274-281. <https://doi.org/10.48528/yhzq-cp97>
- Pinho-Lopes, M., Powrie, W. (2020). Feedback to Students on Soil Mechanics Laboratory Reports- Why Use Virtual Technology if you Can Have a Productive Real Dialogue?. *Proceedings of the 5th International Conference on Geotechnical Engineering Education*, Pantazidou, M., Calvelo, M., Pinho Lopes, M. (Eds.), pp. 228-241, ISSMGE, Athens, Greece.
- Putra, P. D. A., Sulaeman, N. F., Supeno, Wahyuni, S. (2021). Exploring students' critical thinking skills using the engineering design process in a physics classroom. *The Asia-Pacific Education Researcher*, pp. 1-9.
- Qadir, J., Yau, K. L. A., Imran, M. A., Al-Fuqaha, A. (2020). Engineering education, moving into 2020s: Essential competencies for effective 21st century electrical & computer engineers. In 2020 IEEE Frontiers in Education Conference (FIE) (pp. 1-9). IEEE.
- Ralston, P. A., Bays, C. L. (2013). Enhancing critical thinking across the undergraduate experience: An exemplar from engineering. *American Journal of Engineering Education*, 4(2), pp. 119-126.
- Salgado, R. (2022). *The engineering of foundations, slopes and retaining structures*. CRC Press, Boca Raton, Florida, United States of America.
- Schweiger, H. F., Fabris, C., Ausweger, G., Hauser, L. (2019). Examples of successful numerical modelling of complex geotechnical problems. *Innovative Infrastructure Solutions*, 4, pp. 1-10.
- Shiau, J., Lamb, B., Sams, M. (2016). The use of sinkhole models in advanced geotechnical engineering teaching. *GEOMATE Journal*, 10(20), pp. 1718-1724.
- Silber-Varod, V., Eshet-Alkalai, Y., Geri, N. (2019). Tracing research trends of 21st-century learning skills. *British Journal of Educational Technology*, 50(6), pp. 3099-3118.

Authors' bios

Margarida Pinho-Lopes, University of Aveiro (Portugal)

Margarida Pinho-Lopes is an Assistant Professor at the Department of Civil Engineering at the University of Aveiro, Portugal, and a Visiting Academic at the University of Southampton, United Kingdom. Her research work is on geotechnical engineering, particularly on the application of geosynthetics. Her current research interests include numerical models for geosynthetics, nature-based solutions for soil reinforcement, sustainable geotechnical solutions, and geotechnical engineering education. In this area, Margarida has experience with student-centred learning models (problem- and project-based learning, team-based learning, experiential learning), feedback practices, and outreach activities. She is involved in projects related to pedagogical innovation in higher education. She is a member of ISSMGE TC306 Geoenvironmental Education, a Fellow of AdvanceHE (formerly, Higher Education Academy, UK) and of the Portuguese Society for Engineering Education (SPEE). Margarida is a member of the Pedagogical Board of University of Aveiro. She received the New Frontiers of Engineering – Higher Education Teachers award (2012, 2016, 2023) by the Portuguese Institution of Engineers (Ordem dos Engenheiros). She received the Good Pedagogical Practices Award from the University of Aveiro in 2022 and an Honourable mention in 2021.

Joaquim Macedo, University of Aveiro (Portugal)

Joaquim Macedo is an Assistant Professor in the Department of Civil Engineering, University of Aveiro, where he completed his PhD in 2013 on the topic of road traffic microsimulation. He works in the fields of transportation infrastructures and geotechnics and teaches several courses on those topics. He is the supervisor of ongoing PhD and master's students and was supervisor and co-supervisor of several concluded master's theses. His main research interests are Traffic Engineering, namely the area of traffic modelling, didactics in higher education, and geotechnics applied to transportation infrastructures. Since 2007, he has been implementing active learning strategies in the courses he teaches, especially project-based learning and team-based learning. He is currently involved in projects related to pedagogical innovation in higher education. He is also a member of the Portuguese Society for Engineering Education (SPEE), the UA pedagogical innovation support team and is author of several publications on engineering education. Joaquim has received the New Frontiers of Engineering – Higher Education Teachers award (2012, 2016, 2023) by the Portuguese Institution of Engineers (Ordem dos Engenheiros). He has received an Honourable mention in Good Pedagogical Practices Award from the University of Aveiro in 2021.

Steady-state groundwater flow - combining physical models, hand-drawing and numerical solutions to study plane flownets

M. Pinho-Lopes^{1,2} & W. Powrie²

¹ CERIS and RISCO, Department of Civil Engineering, University of Aveiro, Aveiro, Portugal
mlopes@ua.pt

² School of Engineering, University of Southampton, Southampton, United Kingdom
M.Pinho-Lopes@soton.ac.uk, W.Powrie@soton.ac.uk

ABSTRACT: Many problems in geotechnical engineering are related to groundwater. Thus, graduates should have a sound understanding of the principles of effective stress and groundwater flow and control. A good understanding of groundwater flow, particularly at undergraduate level, can be developed by studying steady-state groundwater flow and calculating associated pore water pressures and flow rates. This paper presents an approach adopted by the authors to promote deep learning of steady-state groundwater flow, which combines three methods: 1) observation of small-scale physical models; 2) hand-drawing plane flownets; 3) comparing results with those obtained from numerical models. The methods adopted are chosen to clarify meaning and cater for different learning styles and preferences. The learning materials adopted include visual, aural and text-based formats. While engaging with the learning material, students practice visual thinking and communication and develop visual literacy, engineering judgement and competence in critical analysis. Numerical tools can be adopted using a teacher- and student-led approach. Based on their experience, the authors recommend using a variety of methods to promote learning and understanding of steady-state groundwater flow and, particularly, drawing flownets.

Keywords: Numerical modelling, Boundary conditions, Confined flownet, Unconfined flownet

1 Introduction

Saturated soils are two-phase materials, formed of soil particles (grains) and pore water. The latter has a significant impact on the overall behaviour of soil and, consequently, of geotechnical structures. Thus, graduates should have a sound understanding of the principles of effective stress and groundwater flow and control. A good understanding of groundwater flow, particularly at undergraduate level, can be developed by studying steady-state groundwater flow and calculating associated pore water pressures and flow rates. Usually, an introductory course in Soil Mechanics includes a module that addresses steady-state groundwater flow. At the end of such a module, students should be able to: i) hand-draw plane flownets for a variety of boundary conditions, in both confined and unconfined situations; ii) use the hand-drawn flownet to calculate flow rates and pore water pressures, and to assess the stability of an excavation floor or sideslope (these are some of the learning outcomes given in Powrie, 2014). This paper focuses on an approach adopted by the authors to promote deep learning of steady-state groundwater flow. The approach proposed combines three methods that address different learning styles and are complementary. These methods are: 1) observation of small-scale physical models, 2) hand-drawing plane flownets, and 3) comparing the results with those from numerical models. The following sections describe these different methods, their corresponding learning goals, and how they can be combined to promote deep learning.

2 Background

Effective engineering and, of course, geo-engineering education, requires authentic learning. In this mode of instruction students explore, discuss, and meaningfully construct concepts and relationships for real-world problems and projects (Donovan et al., 1999). Among other objectives, in higher education authentic learning aims to promote the application of knowledge to real-life contexts, while producing knowledge that can be used by both internal partners (e.g., a university department) and external stakeholders, such as businesses, community groups and charities (Pitchford et al., 2021). This mode of instruction allows for the development of competences and skills that are not addressed by more traditional approaches. However, creating opportunities for authentic learning within base courses can be challenging, as students' prior knowledge may not be sufficient.

Nevertheless, a deep approach to learning is fundamental to develop sound knowledge in geo-engineering. While a focus on isolated elements, aiming to rote-learn, is often associated with surface learning, deep learning involves making connections between concepts and knowledge and gaining meaning and significance (Butcher et al., 2020). Moreover, deep learning is usually considered successful learning, i.e., a sound foundation for further learning. Entwistle & Peterson (2004) present a summary of guidelines for promoting learning environments that support deep learning. These include: 1) providing generative topics and understanding aims, and regularly coming back to them; 2) relating teaching to prior knowledge and to those aims; 3) identifying difficult knowledge and foundational concepts; 4) teaching in a way that clarifies meaning and triggers the interest of diverse students; 5) providing selected examples, to promote the development of correct concepts; encouraging study that includes reflection, metacognitive awareness, and self-regulation; 6) providing opportunities for group discussion (namely of content and learning processes); 7) introducing formative assessment and timely feedback; 8) making available assessment rubrics; 9) implementing assessment methods that boost and reward conceptual understanding; 10) creating opportunities to challenge students; and 11) ensuring constructive alignment of aims with teaching, assessment, and student support.

Butcher et al. (2020) point out that a learning opportunity (e.g., a lecture, a seminar or online learning) may not result in the same degree of learning for both individual students and groups of students enjoying that opportunity. Further, individual preferences, styles, and motivations influence which is the best approach for students. Nevertheless, some factors can consistently promote learning. According to Butcher et al. (2020), those factors are: 1) building on previous knowledge and ideas (constructivism); 2) setting learning outcomes that are linked to assessment criteria and rubrics; 3) including processing activities, which allow discussing and testing ideas and concepts; 4) defining application activities, which include facing challenges by using ideas and, thus, extending and enhancing understanding; 5) clarifying relevance, so students can understand how different courses, contents or activities are linked; 6) creating structure, to help students navigate concepts in an organised and sequenced pathway; 7) providing feedback on learning, which needs to be timely and include information on the success of the learning; 8) providing resources necessary for the task; 9) adjusting and informing students of the time expected per task; 10) providing a support structure, on both academic and personal dimensions of academic life; 11) promoting motivation, both intrinsic and extrinsic; 12) allowing for differentiation within the group of students.

Based on research on cognitive processes, Weinstein et al. (2018) identified six strategies for effective learning (explained in Table): spacing practice, interleaving, elaborating, giving concrete examples, dual coding and practicing retrieval. Combining different strategies creates conditions for long-term retention of information, and deep learning.

Table 1. Six strategies for effective learning (adapted from Weinstein et al. (2018))

Learning strategy	Description
Spacing practice	Spread study activities over time
Interleaving	Switch between topics while studying
Elaborating	Ask and explain why and how things work
Giving concrete examples	Illustrate abstract concepts with specific examples
Dual coding	Combine words and visuals
Practicing retrieval	Bring learned information to mind from long-term memory

To reach a wide variety of students, diverse learning needs and preferences need to be catered for. This can be done by assuming all learning preferences are represented in a particular student body, hence learning materials should be available in a range of formats (Butcher et al., 2020): visual (images, video, multimedia resources), aural (verbal, sound recordings, radio), text-based (written materials, books from which to read), kinesthetic (touch, in-class demonstrations, practical work). In addition, each course should allow students to study at different times and in different places, for example by allowing students to engage with learning materials outside class by making materials available via virtual learning environments. Christidou (2020) pointed out the need for preparing students to master a wide variety of representational modes (e.g., language, image, sound, movement), i.e., to be multiliterate. Engineers need to communicate and think visually; thus, that set of competences must be developed.

The concept of visual literacy emerges as a key set of competences for engineering students that includes the interpretation and transmission of information through images, as well as visual thinking and learning (Martín Erro & Menéndez-Pidal, 2024). A competence framework of Visual Literacy for Engineering Education (VLEE) has been proposed (Martín Erro et al., 2022). The framework encompasses a three-level model to support educators when developing and assessing visual competences of students. The basic level refers to the acquisition of new concepts and the initiation of basic visual and graphic practices. Then, at the intermediate level, these visual and graphic practices are applied, enlarged and organised. Finally, the competent level involves the ability to transmit knowledge, to use critical judgement and develop new practices.

Vitali et al. (2023) point out the need to expose students (undergraduate and graduate) to computational methods and software used in industry. This also allows illustrating fundamental concepts effectively, using numerical modelling programs, and enabling fast parametric analysis. Such features facilitate exploring case studies based on realistic geotechnical engineering design problems. Generating, interpreting and critically analysing visual materials obtained via computational methods and software are key competences for engineers. In the context of Physics courses within engineering programs, Guzman & Juárez (2023) reported issues related to deep learning of basic abilities, including numeric manipulation and mathematical modelling. The authors tried to address difficulties often faced by students in understanding relationships between variables, their behaviour, and their links to mathematical models. For that they developed an approach (Guzman & Juárez, 2023): Learning Science and Engineering with Electronic Spreadsheets Cycle (LSEESC). The learning process of science and engineering concepts should start from physical observation of the phenomena under analysis, describe the numerical behaviour of the variables, and link the results using the mathematical model. Then, students are guided into creating graphical interpretations and perform parametric analysis, by evaluating changes in variables that interact in the problem studied. Finally, a real-world problem is tackled, to apply the concepts learned.

Lyon & Magana (2022) summarised six types of strategies adopted to promote learning of mathematical modelling by engineering students: 1) including a realistic mathematical modelling activity, and potentially 2) extension and creation; 3) ensuring students' background knowledge is adequate; 4) implementing modelling activities in modules, which are 5) sufficiently challenging, and incorporate appropriately difficult concepts; 6) implementing modelling activities as team exercises. Within geotechnical engineering there are examples of using numerical tools to promote learning of modelling. For example, using numerical tools for teaching groundwater flow problems has been reported by Marques (2014) and Vitali et al. (2020).

With the goal of promoting deep learning of steady-state groundwater flow, an approach that combines three methods is presented. Following recommendations from the literature, these methods address different learning styles and are complementary. Processing and application activities are included, as well as opportunities for discussion and extension. Learning materials include different formats and the teaching and learning models adopted follow as much as possible the six strategies for effective learning presented above. A combination of representational modes is included, namely by incorporating computational methods and software used in industry. The strategies used aim to promote learning of modelling by students. The approach and the three methods adopted and described herein are: 1) observation of small-scale physical models, 2) hand-drawing plane flownets, and 3) comparing the results with those obtained from numerical models. The following sections describe these different methods, their corresponding learning goals, and how they can be combined to promote deep learning.

3 Groundwater flow

3.1 Groundwater conditions

Often, groundwater in geotechnical engineering is considered in one of three separate conditions (Atkinson, 2007): i) hydrostatic states; ii) steady-state seepage; iii) consolidating soil. Traditional introductory soil mechanics courses cover these in sequence.

Students are introduced to hydrostatic states, represented by a level water table or phreatic surface (i.e., stationary groundwater), and by hydrostatic pore pressures (u). Pore water pressures are calculated using Equation 1, where γ_w is the unit weight of water and h_w is the height of water above the point of interest.

$$u = \gamma_w h_w \quad (1)$$

Existing hydrostatic groundwater conditions are likely to be affected by excavations or the construction of other geotechnical structures. As a result, variations in pore water pressure away from the hydrostatic condition are likely to cause groundwater to flow. Often, steady-state seepage is associated with a phreatic surface that is not level (Atkinson, 2007). Groundwater flow through the soil pores is driven by a hydraulic gradient (Powrie, 2014). The hydraulic gradient is the change of total head (potential), quantified using Bernoulli's expression neglecting the velocity head (Equation 2), as a function of the pressure head (h_w), and the elevation head (z) at the point of interest.

$$h = h_w + z \quad (2)$$

Darcy's Law governs the flow of groundwater through soil and can be represented by Equation 3, where q (m^3/s) is the volumetric flow rate of water, A (m^2) is the cross-sectional area of the flow, $i = -dh/dx$ is the hydraulic gradient (the rate of decrease of total head (potential) with distance in the direction of the flow, x), and k (m/s) is the hydraulic conductivity (sometimes termed the coefficient of, or the Darcy permeability) of the soil in the direction of the flow. Darcy's Law can be applied to two different cases, provided that laminar flow occurs: steady-state seepage of water through a nondeforming soil skeleton; and the transient flow of water being squeezed out from pores between soil particles that are moving closer together as a result of an increase in effective stress (Powrie, 2014).

$$q = Aki = Ak \left(-\frac{dh}{dx} \right) \quad (3)$$

Consolidation is associated with pore pressures changing with time, leading to corresponding changes in effective stresses and soil volumes. Thus, consolidation of soil couples Darcy's seepage theory with soil compression and (if the effective stresses are reducing so that water flows into the soil) swelling (Atkinson, 2007).

As the scope of this paper is the combination of three different methods to study two-dimensional (2D) flownets, the next section briefly presents plane groundwater flow.

3.2 Plane groundwater flow

Most courses on Soil Mechanics at undergraduate level cover soil permeability, seepage and groundwater flow. Simple groundwater flow problems, particularly for plane conditions and steady-state flow, are often solved graphically and/or numerically. These methods are based on the differential equation governing the three-dimensional (3D) flow of groundwater. However, this equation is seldomly used explicitly. In Equation 4, k_x , k_y , and k_z are the soil hydraulic conductivities in the directions of x -, y - and z -axes, respectively. Laplace's Equation is a simplification of Equation 4, for the case soils with isotropic Darcy permeability ($k_x = k_y = k_z$).

$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} + k_{xz} \frac{\partial^2 h}{\partial z^2} = 0 \quad (4)$$

Earthworks such as excavations, cuttings and embankments are often long relative to their cross-section. Thus, seepage flow will occur predominantly in the plane of the cross-section. The 3D flow problem is simplified to a 2D problem, and the differential equation governing flow may be solved graphically.

3.3 Flownet hand-drawing

A flownet is a graphical representation of a 2D seepage regime and is formed by two families of curves: flowlines and equipotential lines. A flowline represents the trajectory of an individual particle of water (or other fluid percolating the soil). An equipotential line links points with the same total head or potential. A flownet may be used to calculate the seepage flowrate and pore water pressures at any point on the cross-section. The tangent to the flowline at a specific point represents the velocity of a water particle at that point, proportional to the hydraulic gradient, and, thus, dependent on the coordinates of the point.

The following conditions must be satisfied when hand-drawing a flownet (Powrie, 2014):

1. Flowlines and equipotential lines intersect at 90° angles.
2. Lines of the same family cannot intersect, i.e., flowlines cannot cross other flowlines, and equipotential lines cannot cross other equipotential lines.
3. Impermeable boundaries and lines of symmetry are flowlines.
4. The lower boundaries of practically static bodies of water, such as reservoirs, are equipotentials.
5. The flownet must be constructed so that each element is a curvilinear square, with curved sides and where a circle may be inscribed.

Two types of flownets can be defined. Confined flownets correspond to problems for which all boundaries of the flow regime are known beforehand. Unconfined flownets include an initially unknown boundary, often in an unconfined or water table aquifer whose soil surface does not remain flooded. Unconfined flownets can be challenging for undergraduate students to draw.

4 Methods adopted

4.1 Observation of small-scale physical models

One of the methods adopted includes the observation of small-scale physical models that illustrate groundwater flow. Using a purpose-built model for each lecture or demonstration session is logistically difficult, and time consuming. Using a video has several advantages, as the video can be played, stopped, continued, and replayed, as necessary. In addition, if students have access to the video, they can replay it while solving exercises and hand-drawing flownets. These features allow directing students' attention to different aspects and to an increasing number of details of a flow and its flownet.

Thus, a video illustrating groundwater flow has been used. The video was produced at the University of Southampton (Robinson and Hammond). The physical model refers to the flow around an impermeable curtain (Figure 2). In preparation for the video, sand was placed in an acrylic box, to different heights on each of the sides of the vertical, impermeable wall. In the video it is possible to watch the water level rising, saturating the soil. Then, a steady state flow is established, visible on the downstream side of the physical model. Later, the flow is illustrated using blue-coloured water, introduced in the soil at different points, to show flow paths corresponding to flow lines in a flownet (Figure 2). Blue-coloured water is introduced in the soil several times, to enable visualisation of more complete flowlines. The difference in velocity between different flowlines can be observed in the video. The flow associated with two different values of overall head difference is also illustrated. Lastly, hydraulic instability (quicksand conditions) is shown, represented by the collapse of a weight placed downstream of the impermeable wall.

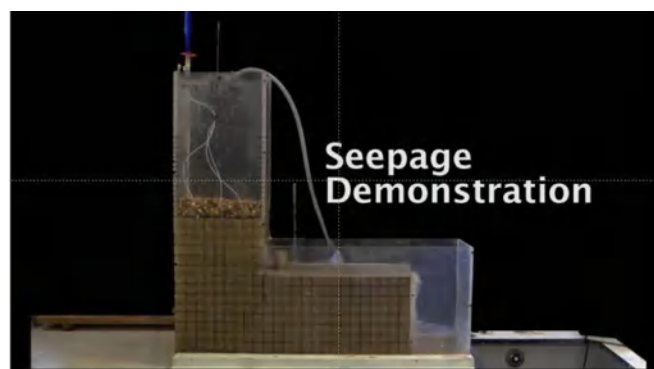


Figure 1. Groundwater flow video demonstration: overview of the small scale physical model

In class, the video is shown to students and narrated by the lecturer. The video is stopped and replayed as necessary. Often, students are questioned, and some large group discussion moments are promoted, to develop explanations for the behaviour observed in the video.

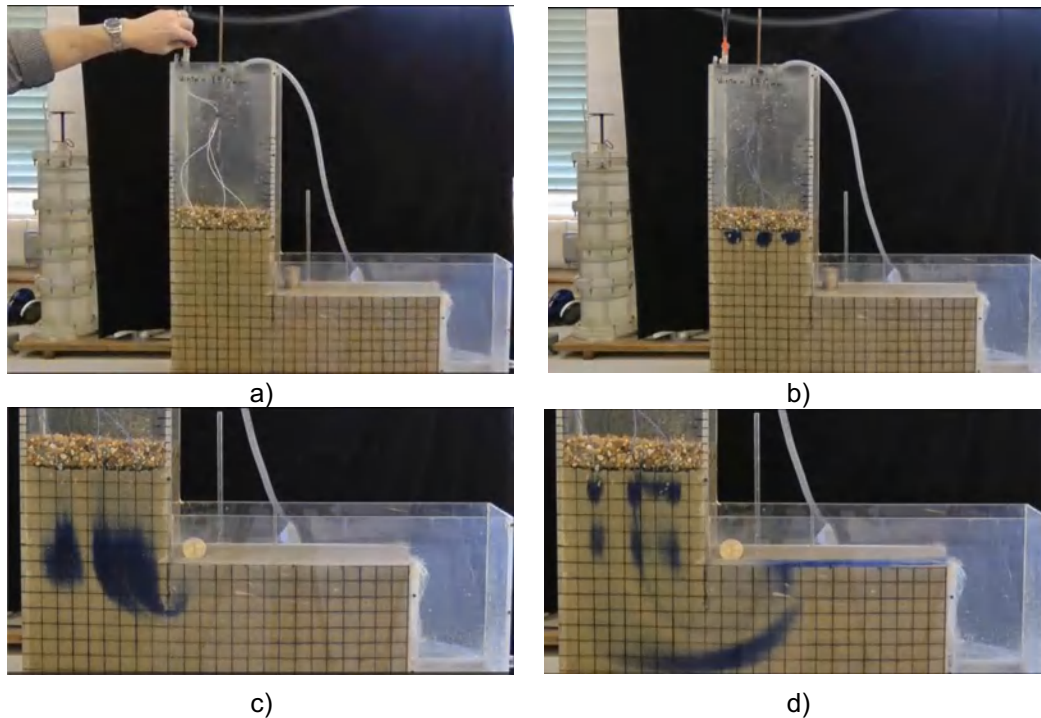


Figure 2. Groundwater flow video demonstration: a) opening valves for adding coloured water; b) three points of entry in the soil of blue-coloured water; c) progress of blue-coloured water close to the impermeable wall and failure of weight downstream, due to hydraulic instability; d) illustration of flow lines

4.2 Hand-drawing flownets

The ability to hand-draw flownets is a key competence that undergraduate students need to develop. The rules for drawing flownets are presented and discussed in-class. As an illustrative example of how to implement those rules, the flownet for a realistic problem (a cofferdam, with a setup similar to that of the video demonstration) is sketched sequentially by the teacher, using a slide presentation (Figure 3).

Then, students tackle problem sheets individually, trying to hand-draw flownets, supported by the lecturer. Students tackle the drawing tasks using pencils and paper or, more recently, tablets and digital pens. This allows students to face an empty sheet of paper (or screen) and try to start the drawing process on their own. During that activity, the teacher moves around the lecture room, helping, asking questions to guide students in relating the rules and their drawings. This allows students to make mistakes, receive feedback, and improve their drawings. There is often benefit in encouraging students to stand at the front of the class and explain / discuss their efforts to peers. Only later, at the end of the lecture, on the following lecture or at the end of the chapter on groundwater flow, hand-drawn solutions are made available to students. Hand-drawing is a trial-and-error process, which can be severely compromised by looking at the final solution before sufficient thought has been applied.

Figure 4 illustrates one of the first flownet hand-drawing problems tackled in-class. Purposely, this initial problem has similarities to the one used for illustrating flownet drawing process and the demonstration video (small scale physical model of groundwater flow). The similarities help overcome the initial difficulties associated with starting to draw a flownet – mainly, “where do I start?”. Another strategy that helps the initial phase of drawing is to suggest the numbers of flowtubes (channels defined by two adjacent flowlines) and of equipotential drops (the number of spaces between equipotential lines) for students to include in the drawing. “Keep it simple” is a further helpful rule.

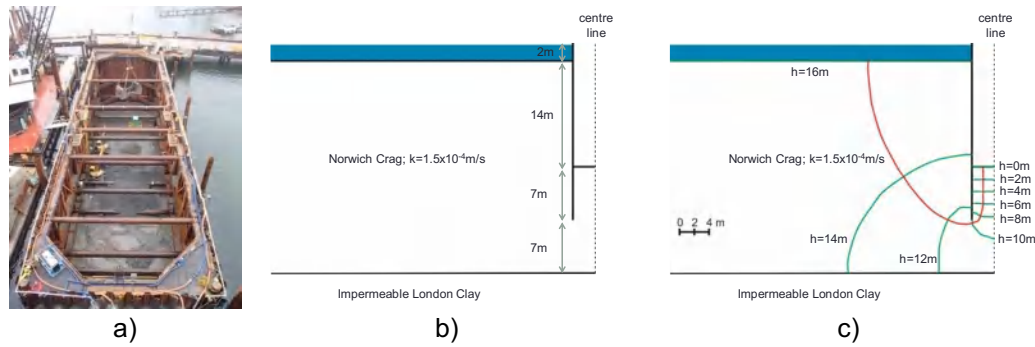


Figure 3. Problem used for illustrating flownet hand-drawing: a) real problem; b) schematic overview of the 2D groundwater flow problem ; c) hand-drawn flownet

Afterwards, students tackle other groundwater flow problems, with different geometries and conditions (including unconfined flownets), and with no predefined number of flowtubes and equipotential drops. They are encouraged to judge for themselves that clay soils can often be considered relatively impermeable, and very coarse soils of fractured rock effectively to act as reservoirs or sinks.

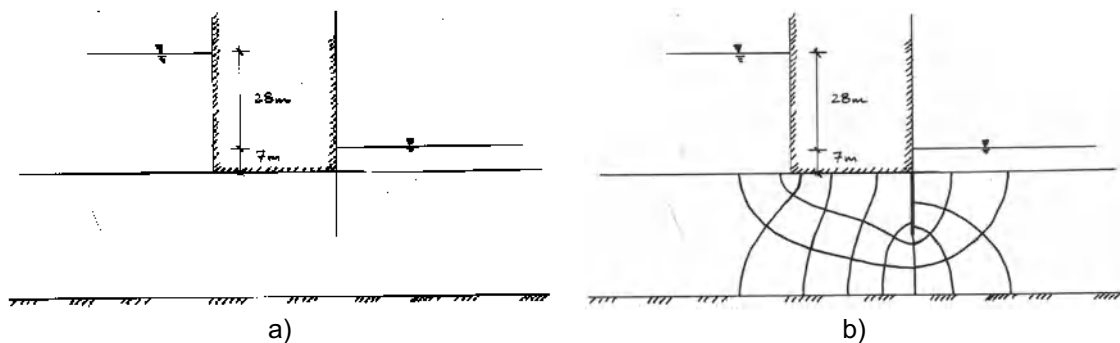


Figure 4. Flownet hand-drawing exercise for students to solve in-class: a) initial problem; b) hand-drawn solution made available to students

Another aspect discussed in class is the influence of anisotropy of soil permeability on groundwater flow and how to consider it when generating flownets. The scale factor to use for hand-drawing this type of flownet is derived in-class. An illustrative example is shown (Figure 5). The flownet in the transformed geometry is drawn, meeting the conditions described in Section 0; the original geometry is reinstated and the properties of the resulting flownet are discussed in-class, pointing out that some conditions are not satisfied. Then, students practice hand-drawing flownets in anisotropic soils.

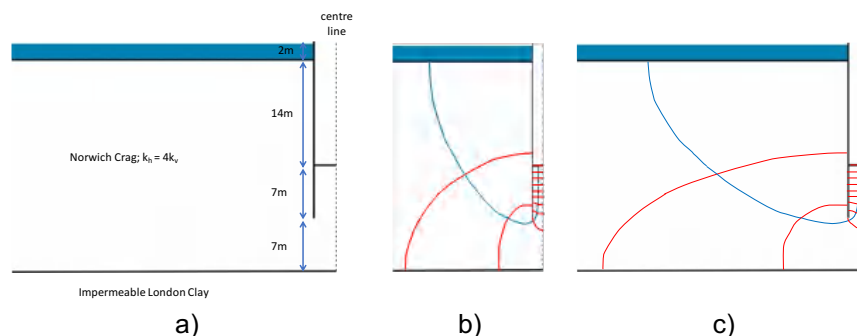


Figure 5. Anisotropy of permeability: a) 2D flow base problem (similar to Figure 3); b) hand-drawn flownet for transformed geometry; c) hand-drawn flownet for original geometry

4.3 Using numerical tools to generate flownets

4.3.1 Approaches adopted

Two approaches are discussed herein: teacher- and student-led. The first was adopted by both authors (between 2015 and 2019 at the University of Southampton). The second has been implemented by the first author (with the collaboration of another colleague) at the University of Aveiro, first in 2008 to 2012 and later between 2020-2024. At the University of Aveiro, these two approaches (teacher- and student-led) were used in parallel. In the teacher-led approach students are passive recipients of information generated using numerical tools, which are then used as educational material. In the student-led approach, students generate their own numerical models and associated flownets. These approaches are briefly described and illustrated in the following subsections.

4.3.2 Teacher-led approach

The authors have used numerical tools and outputs generated using such tools to produce educational material to support teaching and learning. The approach included generating numerical solutions for flownet exercises using software with the finite elements method (GeoStudio). The outputs generated are shown and discussed with students. The aim is to illustrate that what students are drawing by hand (and sometimes struggling with) can be rapidly generated using software. The use of such tools in industry is also discussed, together with the importance of developing critical judgment.

Figure 6 illustrates the flownet obtained using a numerical tool for the illustrative problem tackled in-class (Figure 3) and for the flownet hand-drawing exercise that students solve in-class (Figure 4).

Differences between hand-drawn and the numerically generated flownets shown in class are discussed with students. During these moments, students are challenged to find differences and explain them. To trigger discussion, sometimes clearly different flownets are shown. The goal is to point out key aspects to consider when defining numerical models. Aspects such as the lateral extent of the soil mass and its effect on the shape of the equipotential lines are discussed (Figure 7). Limitations of the software are also drawn out. For example, when using GeoStudio flowlines are not generated numerically, but are drawn on top of calculated data for hydraulic head. This, particularly when combined with a coarse finite element mesh, can lead to flowlines that seem wrong and that do not meet the conditions that must be satisfied when drawing a flownet. Alternatively, flow vectors may be analysed (Figure 8).

The influence of the anisotropy of permeability of soils in groundwater flow is also illustrated in-class using outputs generated with numerical tools. Figure 9 shows examples of flownets generated for the same geometry of the problem represented in Figure 3 but considering anisotropy of permeability or a layered soil profile (two layers of soil each with isotropy of permeability; the hydraulic conductivity of the soil below the excavation base is twice that of the overlying soil). Features of the resulting flownets are discussed in class.

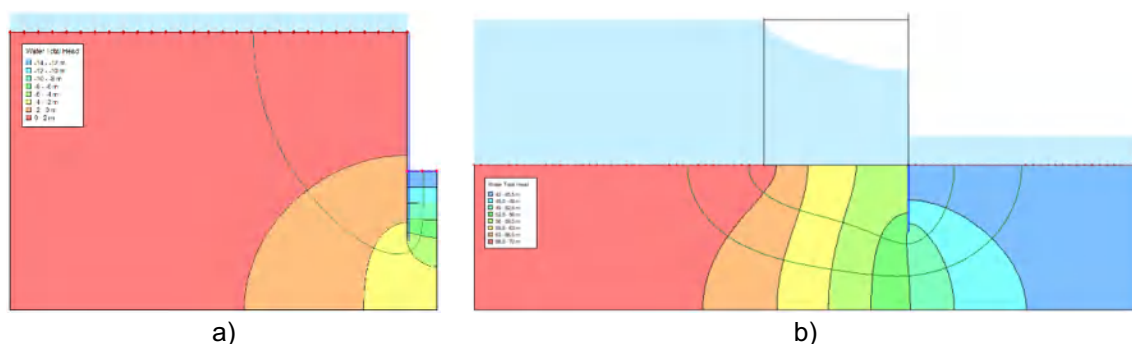


Figure 6. Flownets generated using numerical tools: a) problem used for illustrating flownet drawing (Figure 3); b) flownet drawing exercise for students to solve in-class (Figure 4)

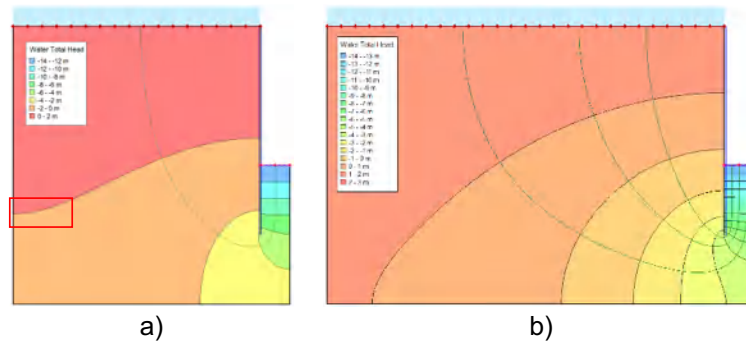


Figure 7. Flownets generated using numerical tools for an illustrative problem (Figure 3): a) smaller area of analysis; b) same solution as in Figure 6 but with higher number of flow tubes and equipotential drops

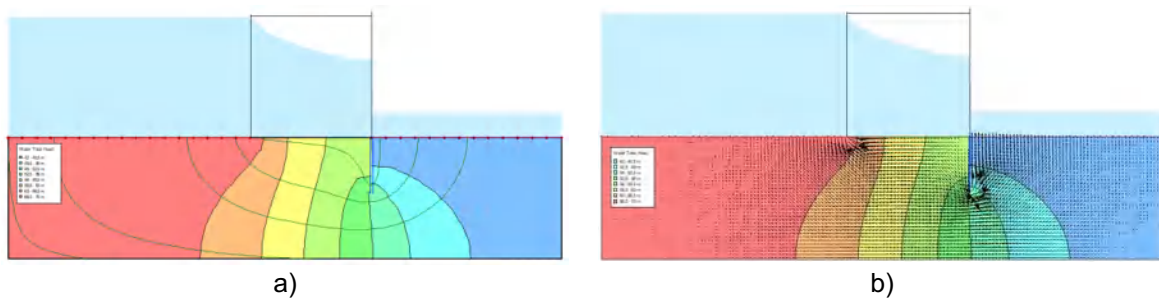


Figure 8. Flownets generated using numerical tools for the problem in Figure 4: a) erroneous flowlines, particularly near the curtain and the boundaries of the model; b) flow vectors (calculated), instead of flowlines (drawn over equipotential lines)

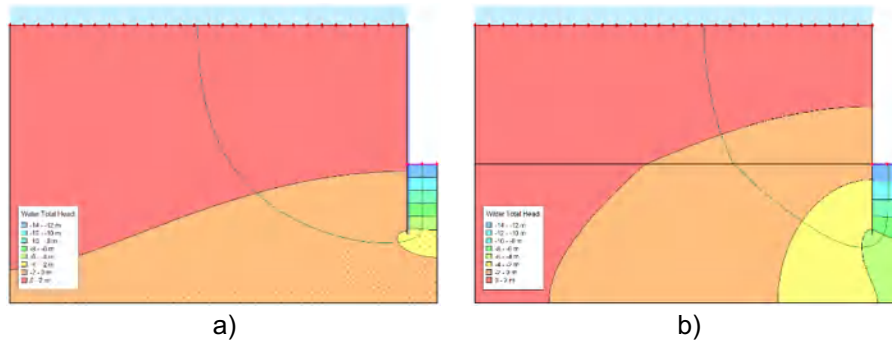


Figure 9. Variations of the problem used for illustrating flownet sketching (Figure 3): a) anisotropy of permeability ($k_h = 4k_v$); b) stratified soil profile (each layer is isotropic; coefficient of permeability of soil above excavation base is double of that of the soil below that level)

4.3.3 Student-led approach

Students were asked to use numerical tools to produce flownets and compare them with given flownets and/or the ones they hand-drew. The data were generated while developing a small team project (within the scope of project-based learning, namely a simple version of that described by Pinho-Lopes & Macedo (2016)). Students were invited to hand-draw and use numerical models to obtain flownets. The main educational goals are to promote effective, deep learning on how to generate flownets using different tools, and to develop engineering judgement by critically comparing results.

To guide students into using Geostudio (SEEP module, for groundwater flow), a variety of resources has been made available: i) from the software provider, such as video tutorials, and example files; and ii) produced at University of Aveiro (video tutorials). The latter demonstrate how to generate flownets using Geostudio for a simple example, highlighting different ways of implementing changes in the

numerical models to rapidly carry out parametric analysis; these include changing the geometry of the problem, and thus the soil mass analysed, boundary conditions, or relevant soil properties. The video tutorials also covered aspects related to the visualisation and extraction of results.

Students do not have any course on finite elements beforehand, so they are using the numerical tool as a black box. This creates additional challenges, as students do not yet grasp which parameters may influence results. The video tutorials, prepared as guides for students, try to address some of those aspects. Relative to the domain discretisation and the finite element mesh, Geostudio uses square elements. The only mesh-related attribute that can be changed by a user is the element size. Some recommendations on that choice are given in the video tutorials and/or tutorial session. Aspects related to the area of analysis to consider are examined at different times. First, when the teacher-led approach is implemented, the influence of the dimension of the area of analysis is discussed and illustrative examples are shown (Section 0). The definition of the boundary conditions (applicable to groundwater flow, steady-state problems) is discussed in detail. This includes addressing the implementation of key boundary conditions in the illustrative examples used in the tutorial videos or sessions, such as draining elements and reservoirs of water.

The course brief of the small team project (that is, the base problem for which a new flownet is to be generated) changes every year. As an illustrative example the base problem proposed in 2024/2025 (at University of Aveiro) is shown in Figure 10, and includes flownets generated by students using hand-drawing and the selected commercial software.

In some years, depending on the time available for students to develop the coursework, soils with anisotropy of permeability and/or layered soil profiles are also analysed. The use of software by students enables exploration of more complex scenarios, difficult to solve using hand-calculations or available solutions.

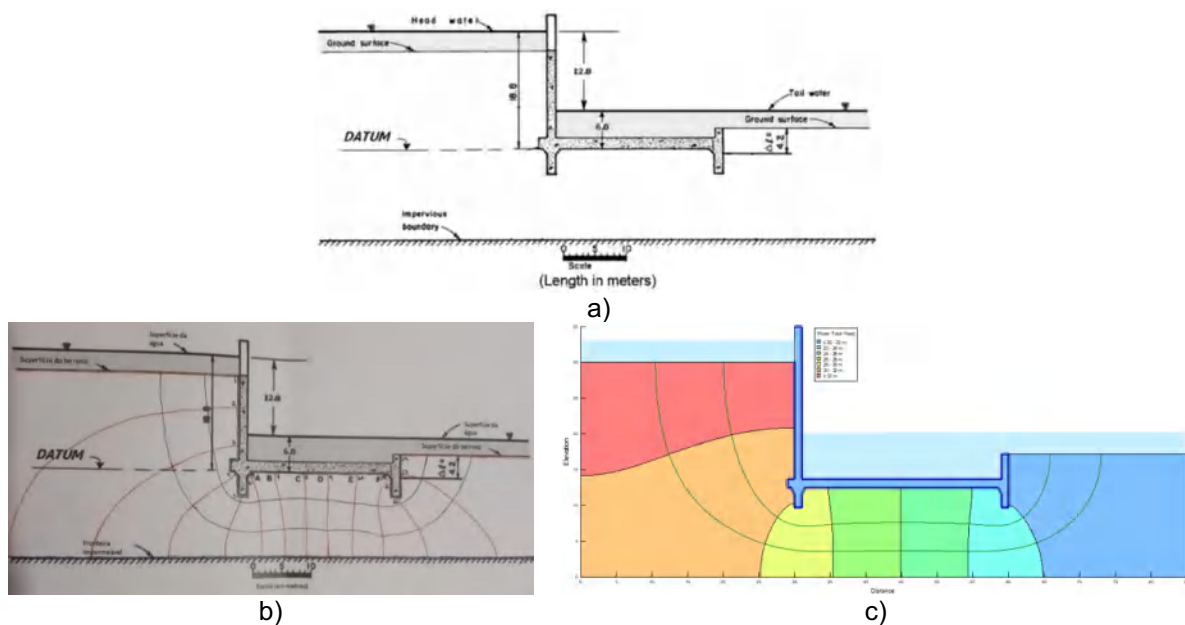


Figure 10. Base problem for flownet drawing by students (project-based learning, 2024/2025): a) overview (adapted from Kaliakin, 2017); b) flownet hand-drawn by a group of students; c) flownet generated numerically by the same group of students

To give timely and effective feedback, the authors developed an approach (Pinho-Lopes & Powrie, 2020) that helps deconstruct misconceptions and errors made by students when generating flownets. Feedback sessions, in which each group of students meets with a lecturer to discuss their project, have been shown to be effective in promoting learning. The lecturer can use questions to promote critical thinking and the development of engineering judgement. Often these discussion sessions generate a Eureka moment, as students finally bring different concepts together.

5 Discussion

The methods adopted have been chosen to clarify meaning and to cater for different learning styles and preferences. The use of similar, simple examples in the different teaching methods described helps to develop and reinforce correct concepts. When challenged to compare results obtained using different methods, students are encouraged to reflect, both individually and as a class or a small team, and engage in group discussions (in class and during the development of the small team projects). Hand-drawing flownets gives students the opportunity to test ideas and concepts but also to face challenges as they attempt problems of increasing difficulty, always supported by the teacher. The introduction of in-class discussion moments creates opportunities for elaboration, based on concrete examples.

The methods adopted combine words (oral and written) and visuals, with images provided to students and generated by students (hand-drawn and/or with numerical tools). The learning materials adopted include visual, aural and text-based formats. Moreover, while engaging with the learning material students practice visual thinking and communication and develop visual literacy. This includes activities at the three levels of visual competences: 1) acquisition of new concepts and initiation of basic visual and graphic practices (e.g., observation of small-scale physical model and sketching simple flownets); 2) application of visuals is progressively enlarged and organised (e.g., students tackle exercises with increasing degree of complexity); 3) transmission of knowledge, use of critical judgement and development of new practices (e.g., in-class and small group discussions, critical comparison of visuals generated using different methods).

For the use of numerical tools with the student-led approach, the introduction of feedback sessions is pivotal in promoting understanding, reflection and self-regulation. To ensure that the modelling activities promote learning, team projects include realistic modelling scenarios, appropriate to the background knowledge students have at that time. The modelling activities are introduced progressively and challenge students, while adding relevance to the topics covered.

The student-led approach in particular allows students to engage with numerical tools. Nevertheless, the goal is to teach students how to use a finite element application effectively, avoiding misuse, rather than making them experts on finite element methods.

When comparing the adoption of numerical tools, the teacher- and student-led approaches can be complementary. In the teacher-led approach, there is more control over what students see and the examples to which they are exposed. It also allows coverage of key aspects of the syllabus in a timely manner. However, if students are only shown and told about the educational materials generated using numerical tools, their learning is more passive hence more challenging for students to effectively construct their knowledge on the topic.

Conversely, the student-led approach is an active form of learning that promotes the development of additional competences and skills (such as those associated with the use of numerical tools). Nevertheless, students may not check all the intended scenarios, even if the project brief is crafted to trigger that. Adequate scaffolding is key to promoting the effective use of numerical tools by students without the formal theoretical background to the numerical tools adopted. If timely and effective feedback is not given to students, the approach can create additional misconceptions and propagate errors.

6 Conclusions

The approach described herein involves the use of different methods for promoting competence development within the context of groundwater flow and associated 2D flownets. The use of different but complementary methods is described: observing small-scale physical models, hand-drawing flownets, and using numerical tools (in both teacher- and student-led approaches) to generate flownets. Based on their experience, the authors recommend using a variety of methods to promote learning and understanding of steady-state groundwater flow and, particularly, drawing flownets.

Acknowledgments

This work was supported by FCT – Fundação para a Ciência e Tecnologia, I.P. by project reference UIDB/04450/2020 and DOI identifier 10.54499/UIDB/04450/2020 (RISCO) and through the project UIDB/04625/2025 of the research unit CERIS.

References

- Atkinson, J. (2007). *The Mechanics of Soils and Foundations*. 2nd Edition. CRC Press, London, United Kingdom.
- Butcher, C., Davies, C., Highton, M. (2020). *Designing learning: from module outline to effective teaching*. Second edition. Routledge, London, United Kingdom.
- Christidou, V. (2020). When Graphs are More than 'Pictures': Visual Literacy as a Challenge for STEM education. *Proceedings of the 5th International Conference on Geotechnical Engineering Education*, Pantazidou, M., Calvelo, M., Pinho Lopes, M. (Eds.), pp. 26-37, ISSMGE, Athens, Greece.
- Donovan, M.S., Bransford, J.D., Pellegrino, J.W. (Eds.). (1999). *How people learn: Bridging research and practice*. National Academy Press, Washington, DC, United States of America.
- Entwistle, N.J., Peterson, E.R. (2004). Conceptions of learning and knowledge in higher education: Relationships with study behaviour and influences of learning environments. *International Journal of Educational Research*, 41(6), 407-428.
- Guzmán, D.S., Juárez, E.C. (2023). Developing the numeric reasoning and mathematical modeling processes in engineering students using the LSEESC methodology. *Proceedings of 2023 IEEE Frontiers in Education Conference (FIE)*, pp. 1-5, IEEE, College Station, TX, United States of America.
- Juárez E.C., Guzmán, D.S. (2023). Learning Science and Engineering with Electronic Spreadsheets Cycle: A methodological proposal. *Physics Education*. 58(2), 025010.
- Kaliakin, V. (2017). *Soil Mechanics: calculations, principles, and methods*. Butterworth-Heinemann, Amsterdam, Netherlands.
- Lyon, J.A., Magana, A. J. (2020). A review of mathematical modeling in engineering education. *International Journal of Engineering Education*, 36(1), 101-116.
- Marques, J.C. (2014). Experimental modelling vs. numerical simulation in geotechnical training. *Proceedings of 2014 IEEE Global Engineering Education Conference (EDUCON)*, pp. 991-994, Istanbul, Turkey.
- Martín Erro, A., Nuere Menéndez-Pidal, S. (2024). How visual literacy is developed through Engineering Graphics subjects. *Journal of Visual Literacy*, 43(1), 29–45.
- Martín Erro, A., Nuere Menéndez-Pidal, S., Díaz-Obregón Cruzado, R., Acitores Suz, A. (2022). A framework for visual literacy competences in engineering education. *Journal of Visual Literacy*, 41(2), 132–152.
- Pinho-Lopes M., Macedo, J. (2016). Project-based learning in Geotechnics: cooperative versus collaborative teamwork. *European Journal of Engineering Education*, 41(1), 70-90.
- Pinho-Lopes M, Powrie W (2020) Feedback to Students on Soil Mechanics Laboratory Reports- Why Use Virtual Technology if you Can Have a Productive Real Dialogue?. *Proceedings of the 5th International Conference on Geotechnical Engineering Education*, Pantazidou, M., Calvelo, M., Pinho Lopes, M. (Eds.), pp. 228-241, ISSMGE, Athens, Greece.
- Pitchford, A., Owen, D., Stevens, E. (2021). *A handbook for authentic learning in higher education: Transformational learning through real world experiences*. Routledge, London, United Kingdom.
- Powrie, W. (2014). *Soil mechanics: concepts and applications*. 3rd Edition. CRC Press, London, United Kingdom.
- Vitali, O. P., Getchell, A., Santagata, M. (2023). Early Exposure to FEM to Enhance Undergraduate Engagement in Geotechnical Engineering. *Proceedings of Geo-Congress 2023*, Rathje, E., Montoya, B.M., Wayne, M. (Eds.), pp. 544-553, ASCE, Los Angeles, California, United States of America.

Vitali, O.P.M., Getchell, A., Santagata, M. (2020). Development of FEM laboratory modules for an introductory undergraduate Geotechnical Engineering course. Lyles School of Civil Engineering Education and Instruction Resources. Paper 1. <https://docs.lib.purdue.edu/civeng-instres/1>

Weinstein, Y., Sumeracki, M., Caviglioli, O. (2018). Understanding how we learn: A visual guide. Routledge, London, United Kingdom.

Authors' bios

Margarida Pinho-Lopes, University of Aveiro (Portugal)

Margarida Pinho-Lopes is an Assistant Professor at the Department of Civil Engineering at the University of Aveiro, Portugal, and a Visiting Academic at the University of Southampton, United Kingdom. Her research work is on geotechnical engineering, particularly on the application of geosynthetics. Her current research interests include numerical models for geosynthetics, nature-based solutions for soil reinforcement, sustainable geotechnical solutions, and geotechnical engineering education. In this area, Margarida has experience with student-centred learning models (problem- and project-based learning, team-based learning, experiential learning), feedback practices, and outreach activities. She is involved in projects related to pedagogical innovation in higher education. She is a member of ISSMGE TC306 Geoengineering Education, a Fellow of AdvanceHE (formerly, Higher Education Academy, UK) and of the Portuguese Society for Engineering Education (SPEE). Margarida is a member of the Pedagogical Board of University of Aveiro. She received the New Frontiers of Engineering – Higher Education Teachers award (2012, 2016, 2023) by the Portuguese Institution of Engineers (Ordem dos Engenheiros). She received the Good Pedagogical Practices Award from the University of Aveiro in 2022 and an Honourable mention in 2021.

William Powrie, University of Southampton (United Kingdom)

William Powrie is Professor of Geotechnical Engineering at the University of Southampton, UK, where he served as Dean of the Faculty of Engineering and the Environment 2010-18. His main areas of research are in what have come to be known as Environmental Geotechnics (landfill engineering, waste mechanics and groundwater control) and Transportation Geotechnics, in which he currently holds a major Programme Grant in railway engineering, Track to the Future. He was elected Fellow of the Royal Academy of Engineering in 2009. William is Convenor of the UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC), and leads the UK Rail Research and Innovation Network (UKRRIN) Centre of Excellence in Infrastructure. He is Geotechnical Consultant to groundwater specialists WJ Group, and is currently providing specialist geotechnical advice on HS2. He is author of the textbook Soil mechanics: concepts and applications, now in its third edition. He is a previous winner of the British Geotechnical Association Prize (1994) / Medal (2017), the Institution of Civil Engineers Telford Medal (2001) and John Henry Garrood King Medal (2002), and the Institution of Mechanical Engineers Thomas Hawksley Medal (2008).

Applied numerical analysis in Geotechnical Engineering: a Masters module from the perspectives of the academic, teaching assistant and students

A. Tsiampousi & P. Tantivangphaisal

Imperial College London, London, United Kingdom
aikaterini.tsiampousi05@imperial.ac.uk, pt620@imperial.ac.uk

ABSTRACT: This paper presents the development and delivery of the "Applied Numerical Analysis" module, a core component of the Geotechnical Engineering MSc program at Imperial College London. The module integrates theoretical knowledge with practical skills in using Finite Element Analysis for geotechnical design and assessment. Delivered through a combination of theoretical discussions and practical tutorials, the module emphasises critical thinking, validation of numerical results, and effective communication of findings. Students engage in a hypothetical project involving complex geotechnical challenges, such as tunnel excavation and deep foundations, using Plaxis 2D software. The module's structure, assessment methods, and the role of teaching assistants are discussed, highlighting the interactive and supportive learning environment. Student feedback indicates high satisfaction with the module's content and delivery, underscoring its effectiveness in preparing graduates for diverse roles in the geotechnical engineering industry.

Keywords: Numerical methods, Finite element analysis

1 Introduction

Civil Engineering graduates and postgraduates are increasingly expected to have acquired soft skills during their studies in addition to broad and robust technical skills and knowledge. Use of software can potentially combine both technical and soft skills, and numerical competence is becoming more and more relevant. At undergraduate level, teaching of Geotechnical Engineering has traditionally focused on the technical knowledge required to become a competent Civil Engineer, justified largely by the complexity of soils as engineering materials. It is rare for computer skills specific to Geotechnical Engineering to be developed during undergraduate studies. Vairaktaris et al. (2008) reported that although teaching of Numerical Methods is common in Civil Engineering degrees across Europe, most programmes focus on introductory and structural courses, at least at undergraduate level. Geotechnical numerical modules most commonly form part of postgraduate taught degrees in Europe.

The importance of using engineering computer packages in education was recognised early on. Rose (1978) emphasised the role of formal, university education on their intelligent use and highlighted them as an educational aid. The use of personal computers to create spreadsheets was integrated in the teaching of geotechnical engineering courses as early as the 1990s (e.g., Zoghi, 1996), and the importance of validating the numerical results, especially when provided by software and computer simulations, was highlighted soon after (e.g., Carter et al., 2000). Rothberg et al. (2006) highlighted the supportive role of hand-outs in computer-aided learning, a practice which can easily be disregarded as irrelevant or unnecessary in practical classes. Pinho-Lopes (2012) presented a case study of the use of computer software, including Finite Element (FE) method, in Soil Mechanics courses at undergraduate level, which in addition to the acquisition of soft skills, enhanced student learning. Emphasis was placed on critical thinking and validation through comparison with theoretical solutions, which deepened understanding of both numerical and theoretical approaches. Lemos et al. (2024) recently demonstrated that digital tools effectively aid teaching and understanding of practical problems.

Following the same principles of critical thinking, validation through comparison with theoretical solutions, and development of comprehensive and practical notes, the first author developed the module Applied Numerical Analysis which incorporates and teaches the use of Finite Element Analysis (FEA) in Geotechnical Engineering. The module was developed for the academic year 2021-22 and was delivered online under COVID-19 restrictions. Since 2022-23 it has been delivered in person, entirely in computer classes. The paper presents the contents and delivery of the module as a case study, encompassing the perspectives of the academic, the graduate teaching assistants and the students.

2 Module overview and learning objectives

Applied numerical analysis is a 30 contact hours core module of the Geotechnical Engineering taught MSc degree at Imperial College London (ICL). It provides practical lessons on using hydromechanically coupled FEA for geotechnical design problems in soft ground. Delivered in the second term of the one-year course, it builds on theoretical modules around geotechnical analysis methods, constitutive modelling, soil behaviour and seepage and consolidation taught in the first term. Students are expected to devote 95 hours of study time to the module.

As the roles and responsibilities of the geotechnical engineer in industry practice become increasingly diversified, a greater range of student backgrounds must be catered for both in terms of prior academic qualifications and industry experience. Although early career graduates of the module and the course typically take up technical roles in industry, many also take up roles in management, quality assurance, arbitration, or other specialist disciplines. The technical learning objectives of the module are thus as valuable as the transferable critical thinking skills taught and highlighted by the combination of theory and practice.

The module aims to provide students with the theoretical basis and practical skills that will enable them to achieve a series of learning outcomes. First and foremost, they learn how to employ numerical analysis to address a variety of geotechnical design problems in an urban environment, including tunnel excavations, foundation problems and deep, multi-propped excavations. This is not limited to developing practical skills using a computer software but is fundamentally focused on developing and exercising critical thinking, understanding and selecting the input and questioning and validating the output.

Students are guided to develop their understanding of the ingredients and information required to perform accurate numerical analyses, including mesh quality, initialisation of stresses, selection of constitutive and hydraulic models and model parameters, application of appropriate boundary conditions at the appropriate sequence and the accurate and detailed documentation of this sequence, and selection of suitable elements to represent structures and their properties and engineering behaviour.

Further to identifying the required input information, students identify output information required for design, and learn to post-process, analyse and communicate the output data in an effective manner. Finally, through comparisons between numerical and theoretical approaches, students identify the advantages and limitations of both, with the ultimate goal of becoming equipped to select between solution methods and compare their outcomes.

3 Practical project brief

During the module students discuss, prepare and run a FEA of a geotechnical problem combining shallow foundations, tunnel excavations, multi-propped deep excavations with retaining walls and piles, in a London stratigraphy and in a hydro-mechanically coupled analysis. A new stage of the analysis is discussed first in every session, making links to previously taught material and covering appropriate aspects of numerical analysis theory, followed by a practical tutorial, preparing and running the numerical analysis, and discussing its results.

A practical project brief underpins the delivery of the module. Students are asked to work as consultants to an imaginary client who wishes to purchase the buildings outlined in black thick line in Figure 1(a), on Oxford Street in central London and redevelop it. For financial reasons, the building is required to have a deep basement and structural engineers have completed the preliminary design of the new building, providing information for the depth, location and properties of all structural elements: retaining walls, temporary props, basement and floor slabs, and piles.

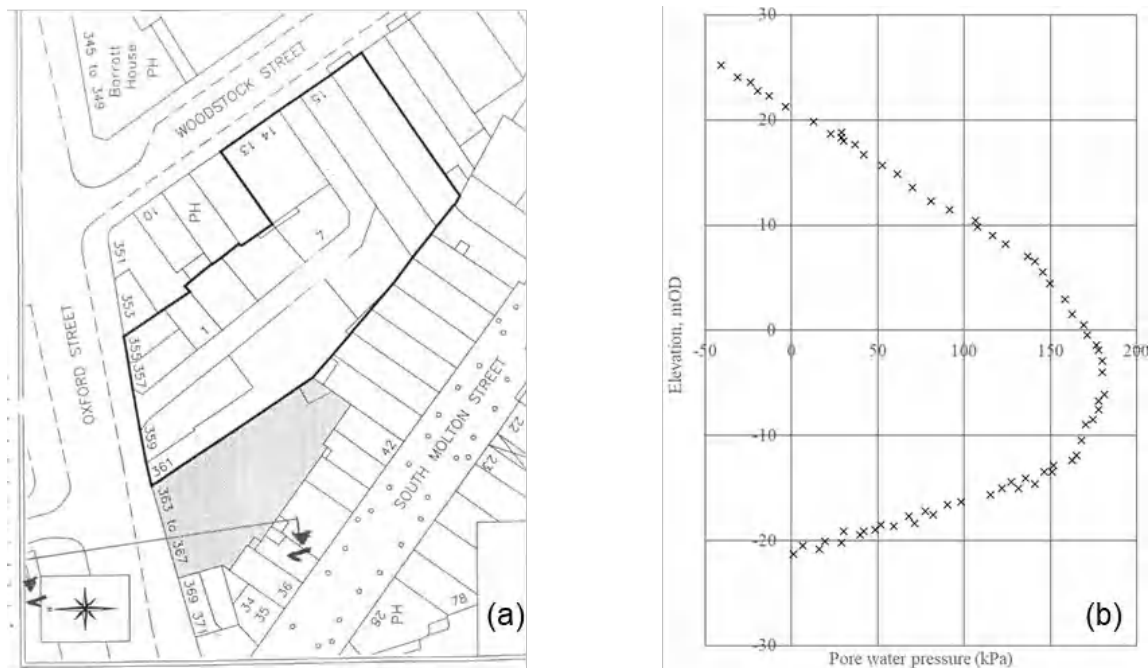


Figure 1. (a) Plan view of the hypothetical site (b) Pore water pressure profile with depth near the site

Given its proximity to existing London Underground Limited (LUL) twin tunnels running underneath Oxford Street, the client wishes to have a feasibility study performed before deciding to proceed with the purchase. As the client does not yet own the site, site investigation is not possible. In this hypothetical scenario, the students' consultancy firm was involved in the redevelopment of a nearby site (cross-section 1-1 in Figure 1 (a)) with a 2.3 m deep basement some 25 years earlier. Therefore, the stratigraphy, consisting of gravels, clays and sands, and material parameters from past numerical analyses are available from that earlier work. A typical for this central London location underdrained pore water pressure profile with depth, shown in Figure 1(b), is present on site but had been neglected in the past. The location, geometry and properties of the LUL tunnels are given in the brief. The tunnels were constructed in 1930, followed by the construction of the existing buildings on either side of the road in 1960. The students are tasked with preparing, performing and interpreting a 2D FE plane strain analysis and advising the client with various options on proceeding with the investment.

4 Module structure and content

The module is delivered in ten 3-hour long, weekly sessions, each roughly divided between one to hours of discussion with the Lecturer and two to one hours of practical tutorial led by the Teaching Assistants. The discussion covers the theory, practical decisions on how to dissect and simplify the engineering problem and represent it with equations in the form of constitutive models and boundary conditions in the numerical analysis, limitations of these decisions and alternative modelling strategies. During the tutorials the students implement these decisions with the help of teaching assistants into an FE software (Plaxis 2D; Bentley Systems, 2024).

During the first session, the students study the brief and discuss the main purpose of the analysis; LUL restrictions and why they are in place; the relevance of having been involved in previous work in the area; the significance of previous work having been delivered 25 years ago; what generated the underdrained pore water pressure profile and why it is being maintained; reasons why it had been neglected in the previous analysis and whether doing so had been reasonable, practical and conservative/unconservative. The session then focuses on reproducing the underdrained pore water pressure profile and initialising vertical and horizontal stresses. The hydraulic conditions that are required are emphasised and discussed in detail. During the tutorial the students initialise stresses and pore water pressures in a steady state analysis and back-calculate the permeability of the clay layers that results in close agreement between the site pore water pressures and the computed ones.

Sessions two and three focus on the modelling of the structural components. Going through the brief line by line, all relevant information is extracted and its significance discussed and put into context. An appropriate 2D cross-section is selected and the limitations of representing the problem in plane strain highlighted. The loads from the existing and the new buildings are estimated, and their points of action defined. Elements are selected for the retaining walls, the tunnel linings, the slabs, the props, and the piles, and their properties are determined. Extensive discussion is dedicated to the simplifications involved, as well as to alternative ways of modelling the structural elements and of rendering the retaining walls impermeable in the analysis. The geometry and all structural elements are then inserted into Plaxis 2D and the mesh is generated. Distinction between mesh quality and accuracy of the results is made.

Sessions four and five are dedicated to the construction of the existing tunnels and buildings, and the consolidation period between them, as well as between the construction of the existing buildings and present day. The brief is again consulted and information on the timeline is extracted so that a construction sequence starts to formulate. Distinction is made between undrained and coupled analysis phases, and between the behaviour of drained and underdrained layers during these phases. Volume loss in tunnelling and its numerical simulation are discussed extensively and the computed settlement trough of the first excavated tunnel is compared with the Gaussian trough. While examining critically the results of the first tunnel excavation the students are guided to question the model parameters in the previous, 25-year-old analysis of a nearby site. The model parameters are then refined and the analysis rerun, thus instilling caution against blindly adopting past practices which may have become obsolete with time. While further post-processing the results emphasis is placed on: the arching mechanism around the tunnels; excess pore water pressures generated during undrained phases and dissipated during consolidation periods; the hydraulic boundary conditions around the newly formulated tunnels; the settlements due to the construction of the existing buildings, which are compared with those computed with Boussinesq's theory.

In session six the redevelopment of the building and its long-time performance are simulated and in session seven the analysis results are critically examined in relation to the displacements and stresses around the deep excavation and to the effect that the new building is predicted to have on the existing tunnels. The students are asked to judge the structural integrity of the tunnels during the redevelopment and in the long-term by plotting moment-axial stress (M-N) interaction diagrams and comparing them with the failure envelope. Furthermore, they study the tunnels' displacement and distortion and compare them with limits set by LUL. They are required to make a judgment on the ability of their initial analysis, where soil behaviour was modelled as linear elastic-perfectly plastic (Mohr-Coulomb), to estimate displacements within serviceability limits accurately.

In session eight, the students are introduced to a non-linear elastic-perfectly plastic constitutive model (Taborda et al., 2024a) and to a version of Modified Cam-clay which incorporates non-linear elasticity and a Hvorslev surface (Tsiamposi et al., 2024), both implemented into Plaxis as user-defined soil models (Taborda et al., 2024b). Following the theoretical introduction into the two constitutive models, the students perform single-Gauss-point-analyses to compare them with Mohr-Coulomb in terms of the predicted stress paths, stress-strain curves and stiffness curves in drained and undrained triaxial compression and extension. Normalised stiffness curves for London clay, where the tunnels are located, are compared with published data.

During session nine, the analysis is re-run twice for the two additional constitutive models considered and the analyses results are once again processed and critically examined, with emphasis on the behaviour of the deep excavation and its impact on the tunnels. The tunnel assessment is repeated, and all results are compared with the results of the Mohr-Coulomb analysis. The importance and implications of accounting for the reduction of stiffness with strain from the small- to the large-strain region are highlighted.

In the tenth and final session, the students identify which construction phase is most critical for the tunnels and explore ways of reducing the impact of the deep excavation (propping system, dimensions of the structural elements, top-down construction etc.) Students are encouraged and free to explore different options with little guidance, in order to use creatively their engineering judgement and newly acquired numerical skills. They are asked to provide verbally the client (lecturer) with guidance as to the feasibility of proceeding with the redevelopment as originally planned and propose preliminary suggestions for alternative designs that should be considered.

5 Notes and teaching materials

In addition to the brief, students are given detailed instructions, in the form of hand-outs, on how to implement the various actions on Plaxis. A random but indicative example of an extract is given in Figure 2. Furthermore, students are given a series of questions in the form of slides that the lecturer is using to promote discussion and guide the theory part of the sessions. During practical tutorials, a lead teaching assistant demonstrates live how to follow the detailed instructions, while two more teaching assistants offer one-to-one help and problem solving to the cohort of students (ranging between 20 and 30 depending on the year). Class materials also include the user manuals for the user-defined soil models, excel spreadsheets containing the pore water pressures and sample M-N interaction diagrams. Students are provided with tailored instructions on how to access Plaxis in ICL computers and their own laptops/PCs at home and have access to Plaxis manuals. Although the course utilises a specific software and inevitably some of the terminology used revolves around it, emphasis is placed during teaching on developing general numerical analysis skills. The module is neither conceived nor delivered as a software training course, and students are continuously prompted to identify and appreciate the various biases that may be inserted in the analysis either by default assumptions the program makes or by the options it offers.

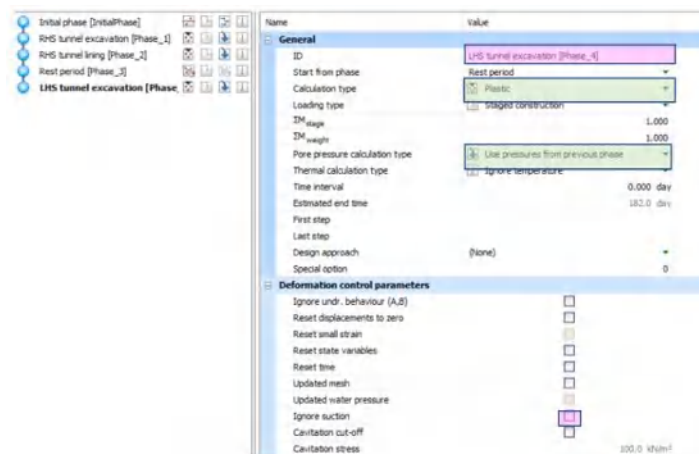


Figure 2. Indicative example of the tutorial instructions hand-outs

6 Assessment and feedback

Formative assessment is carried out continuously during the delivery of the module due to its interactive nature. The theory part of each session starts with targeted oral questions to assess the students' understanding of the material covered in the previous sessions and identify areas that need closer attention. Furthermore, following each session, students are asked to prepare and upload into Blackboard, a customisable online learning tool used broadly for teaching at ICL, answers to specific questions in the form of graphs. These are not marked but used by students to monitor and judge their own progress. They are not compulsory, but as students need to produce them to understand the analysis, most of them upload them to Blackboard as well for ease of future reference.

Summative assessment is split between 9 sessional quizzes (the quiz during the first session is simply formative), totalling 50% of the mark, and a 2-hour computer-based exam which is also worth 50%. Eight out of the nine sessional quizzes are 5 to 15 minutes in duration, worth 5% each, and largely consist of multiple choice, multiply answer, ordering, matching and true/false questions, delivered and largely marked by Blackboard. They are designed to test understanding of the material taught in previous sessions, while prompting students to appreciate the value of being exact rather than vague and conveying wholesome rather than partial answers to questions that may arise during client meetings, either from the client or other structural and geotechnical engineers, while "thinking on one's feet". The quizzes are delivered at the start of each session and answers are discussed straight after, thus also serving a formative role.

The final quiz is one-hour long and worth 10%. It is a mock-up of the final exam and the answers are discussed on the spot. In both of them, students are given a brief and a fully run numerical analysis (i.e.,

students receive a Plaxis file that contains results). The students have to answer questions similar in format to those used in the sessional quizzes, again via Blackboard, which aim to test their ability to understand the numerical analysis that they have been provided with and do so in relation to a specific brief, identify errors, and post-process and interpret results. The exam does not test the students' aptness with the specific software (the analysis is already developed and run) but their knowledge and understanding of numerical analysis. Feedback on the exam is numeric as stipulated by ICL rules, i.e., it is purely summative.

7 Role of the teaching assistants

The graduate teaching assistants (GTA) employed over the past few years have all been current PhD students who utilise, implement and/or develop geotechnical FAE and software in their own research. They are required to be fluent in the operation of the software and to have a strong background in the theory. At ICL, graduate teaching assistants must also complete and pass two compulsory training sessions totalling 6 hours before they are allowed to work. These sessions outline different pedagogical methods, including teaching, assessment and continual feedback and improvement processes. Additional optional training on microteaching, supervision, and active laboratory-based learning are also provided by the university's Graduate School to GTAs.

Typically, each tutorial session involves one teaching assistant taking the lead in a live demonstration of each stage of the numerical analysis. Two assistants roam the classroom to help students via one-to-one consultation during the demonstration, as well as during regular pauses in the session to bring all members of the class up to speed. GTAs are the first port of call for any problems as well as questions linking theory with practice. It is thus vital for them to demonstrate both fluency with the software, an understanding of what "default" settings do, as well as a good knowledge of the theory, modelling assumptions and simplifications. It is emphasised here that these tutorials are not designed nor delivered as software training sessions. Throughout, the students are tasked to think critically about each step of the tutorial, resulting in regular questioning of the provided brief and instructions. The versatility of the software tools available, and the realistic scenario offered by the brief also means the provided instructions is only one out of many possible ways to tackle this tunnel assessment task.

Questions raised to the GTAs by the students have included, for example, the appropriateness and methods to model piled foundations in FE software, the suitability of modelling modern tunnel linings as fully permeable, the construction sequencing of deep foundation with respect to top down and bottom-up basement excavations. Errors in user inputs, how to identify these and their consequences, have also been discussed in detail.

It is important also for the GTAs to understand their own limit of competence and take note to follow up on any particularly tricky questions with the academic and to address these in a subsequent tutorial session. Continuity in the persons delivering the module is also helpful as students often raise similar queries. The geotechnics research section is fortunately large enough for three GTAs at different stages of their PhD studies to be selected each year, with an overlap between different years. The detailed instructions are also developed in part and kept up-to-date by the teaching assistants as they are best placed to take on board the necessary level of detail obtained through students' verbal feedback.

The experience of leading these sessions is also highly beneficial for GTAs with aspirations of an academic career. Although there will always be difficulty in teaching the same content to a student body with diverse learning speeds, adjusting the speed of each tutorial by regularly engaging with each cohort of students before, during and after each session is essential. Good rapport can then be built with the students.

8 Student survey results

The module is subjected to an official survey of each student cohort performed by ICL through a Module Evaluation Questionnaire (MEQ). Questions occasionally change from year to year, with questions added or removed. All students are invited to participate anonymously, but few choose to. Typically, the survey opens after the end of term and remains open until the end of the examination period.

Figure 3 presents official student survey results since 2020-21 when the module was first delivered, entirely online due to COVID-19 restrictions that were in place at the time. Delivery for the current academic year (2024-25) is underway and the survey has not been conducted yet. Students are asked to answer a number of questions by selecting between five options: i. definitely disagree; ii. strongly disagree; iii. neither agree nor disagree; iv. mostly agree; v. definitely agree. All questions are formulated in such a way that “definitely disagree” expresses student disappointment and “definitely agree” denotes student satisfaction.

It is worth highlighting that as it is not obligatory for students to complete the survey, the results presented are based on very small samples, ranging from 17 to 35 students depending on the question, across all years. Nonetheless, the results are highly encouraging, with clear endorsement of the structure and delivery of the module (Figure 3 (a) and (b)).

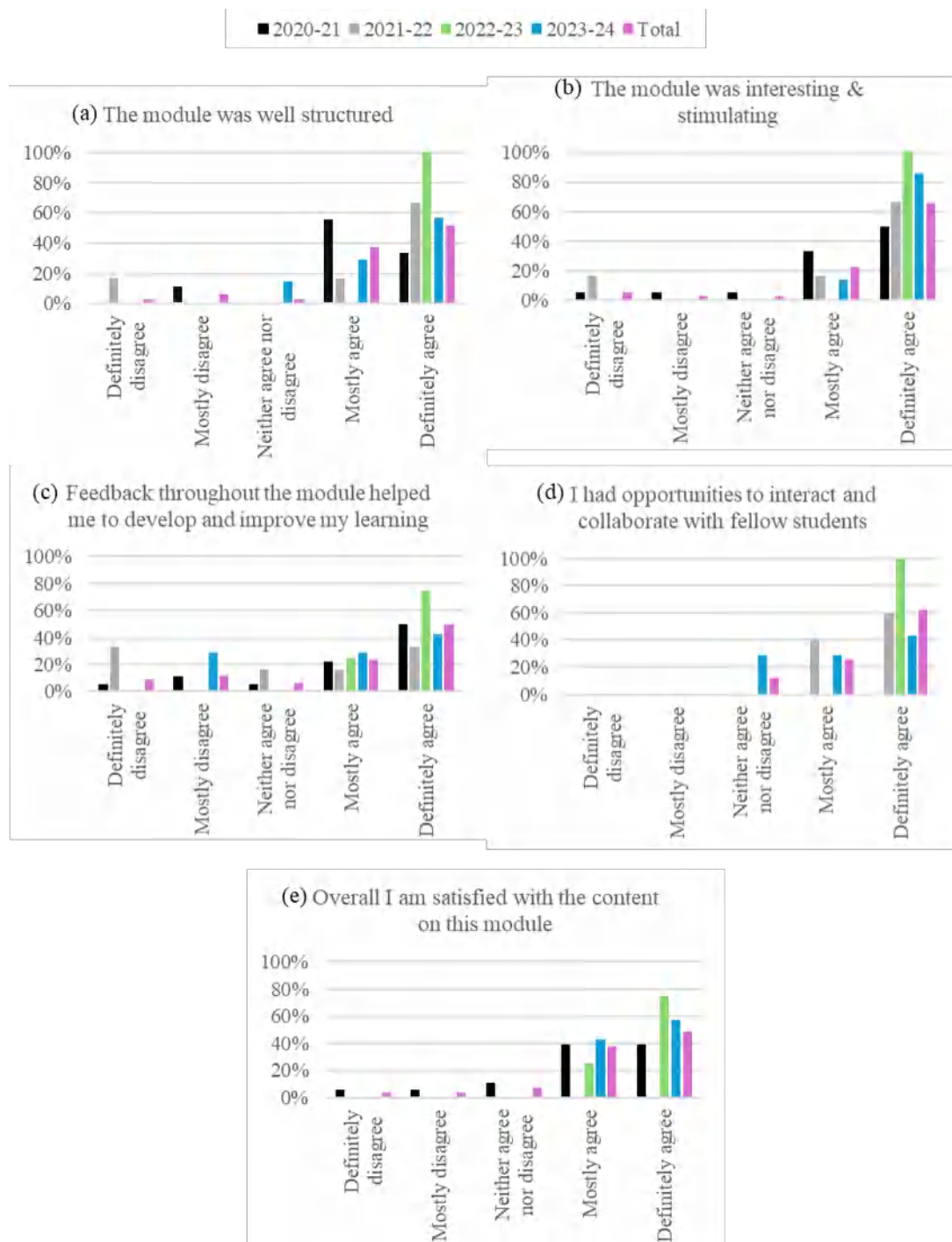


Figure 3. Results of official university surveys. Total number of answers: (a) 35; (b) 35; (c) 34; (d) 17; (e)

Total satisfaction with the usefulness of the feedback is also strong, although this varies from year to year, with 2 out of the 6 students participating in the survey in 2021-2022 indicating strong dissatisfaction. This was the first year that the module was delivered in person, including the sessional quizzes which were at the time the main feedback mechanism. In 2022-23, formative assessment was extended to questions that were not marked and satisfaction with the usefulness of feedback increased and has remained high since, with 74% of the total surveyed students indicating that they either “mostly” or “definitely agree” that the feedback helped them develop and improve their learning.

Students appreciate the interaction and collaboration with their fellow students during the tutorials, as indicated in Figure 3 (d). The lecturer and teaching assistants alike cultivate and promote an environment of close collaboration over competition. Students are encouraged to work closely with their peers, in groups of their choosing, in and out of the classroom, share their analysis and support each other to develop their skills and understanding. Overall, satisfaction with the content of the module is very high (Figure 3 (e)) over the past years.

Moreover, the current (2024-2025) cohort was surveyed anonymously for the purposes of this paper with 12 respondents from 19 students attending this module. Students were given a week to complete the survey during their own time, in between sessions 5 and 6 to fit the timeframe of the Conference. The academic background of half of the respondents originated outside of the UK, with two-thirds having some form of industry experience spanning a range of sectors and roles, from short internships to 14 years of experience. Specific background and previous experience with FEA in geotechnical settings is shown in Figure 4, showing that many students have no formal academic or on-job experience with FEA despite most came to the course with at least some background in industry.

Despite the large range of prior academic and industry experience, the realism of the engineering scenario, pace of teaching, detailed teaching material and instructions, and a combination of theoretical discussion and practical software usage all contribute to the students feeling confident in their own grasp of the content. This is reflected in the survey results in Figure 5 (a) and (b) for both the teaching and practical portions of the module. Even though the module content is provided to the students in its entirety at the start, the majority still uses the tutorial time to complete the exercises, alongside the discussion and peer-to-peer collaboration fostered during these sessions.

Finally, it is also evident from this cohort’s feedback that the utility of the course content is extremely high. The content is well balanced across the different aspects of geotechnical FEA, and students can see clearly the skills gained in the module prepares them well for a career in geotechnical engineering, striking a good balance between theory and practice (Figure 6).

8 Best practice, challenges and lessons learned

The case study highlights effective strategies for teaching numerical modelling in geotechnical engineering. Combining theory with practical application is key. The module’s structure, featuring theoretical discussions and hands-on tutorials, ensures students grasp concepts and apply them in real-world scenarios, enhancing critical thinking and problem-solving skills. Realistic projects, like the hypothetical Oxford Street redevelopment, provide context and relevance, preparing students for industry challenges. Encouraging critical evaluation of past practices fosters a habit of questioning and validating information, crucial for effective engineering. While specific software training is somewhat necessary, the focus should be on general numerical analysis skills, making students adaptable to different tools. Tailoring teaching methods to diverse backgrounds and learning speeds, along with continuous formative assessment and immediate feedback, ensures all students benefit. Knowledgeable teaching assistants enhance learning by linking theory with practice and providing support. Promoting collaboration during tutorials fosters a supportive learning community, improving learning outcomes and developing teamwork and communication skills.

Challenges further to the delivery of the material include licensing and the use of commercial software, which may be expensive. Plaxis 2D was the chosen software for a combination of reasons. It is user friendly and thus time can be devoted to actual learning than to particularities of the software. It is a tool widely used in Industry and, therefore, valued by the students. ICL has secured a good number of licences and managing licences (i.e., distributing them to students and revoking them after the completion of their studies) is relative straightforward. Nonetheless, it should be emphasised that the care should be taken for the module not to dissent to software training course. In our experience, clearly

explaining learning outcomes and setting expectations from the start helps students focus on developing numerical analysis skills beyond just using the software.

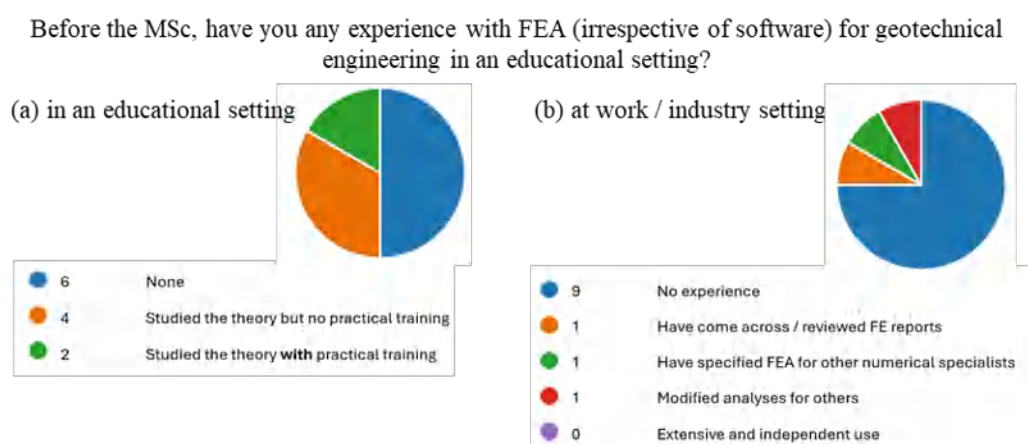


Figure 4. Results of students' previous experience with geotechnical FE analyses. Based on 12 replies

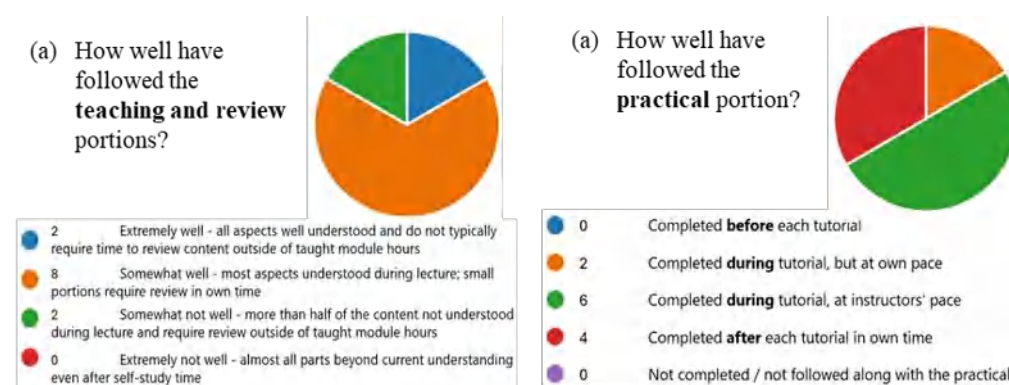


Figure 5. Results of current students' experience. Based on 12 replies

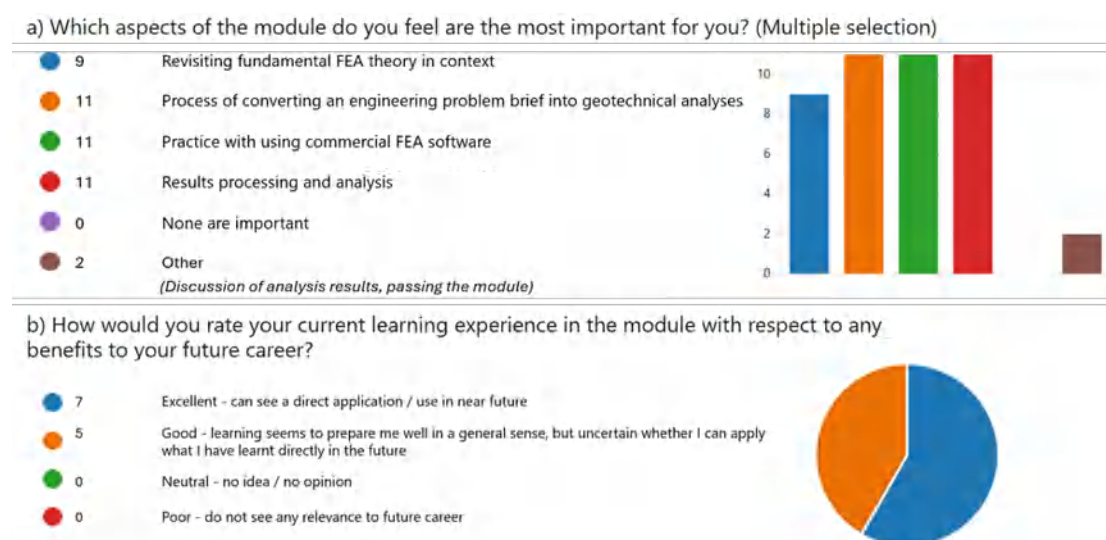


Figure 6. Results of current students' feedback and self-assessed learning outcomes. Based on 12 replies

9 Conclusions

The module Applied Numerical Analysis presented here aims to integrate FEA with real-world geotechnical design problems and equip students with essential skills for their professional careers. Emphasis has been placed on critical thinking and validation of numerical results. Although a specific

software is used, teaching of the module transcends the software and the same learning objectives could be delivered using any other software. By engaging students in realistic projects, such as the hypothetical redevelopment on Oxford Street, the module provides context and relevance, enhancing the learning experience. The continuous formative assessment and immediate feedback mechanisms ensure that students can monitor their progress and address any gaps in their understanding promptly.

The role of teaching assistants is crucial in this module, providing one-on-one support and linking theoretical concepts with practical applications. Their involvement enhances the learning environment, making it more interactive and supportive. Additionally, the module's focus on developing general numerical analysis skills, rather than just software-specific training, ensures that students are versatile and adaptable to various tools and methodologies.

Student feedback indicates high satisfaction with the module's structure, content, and delivery. The collaborative learning environment, fostered by interactive sessions, further enhances the educational experience, preparing students for diverse roles in the geotechnical engineering industry.

Acknowledgements

Drs A. Ruiz Lopez and J. K. Moller, GTAs in 2021-2022, were instrumental in the development and initial delivery of this module. Their assistance is greatly appreciated.

References

Bentley Systems (2024) CONNECT Edition V24.00 PLAXIS 2D Reference Manual.

Carter, J.P., Desai, C.S., Potts, D.M., Schweiger, H.F., Sloan, S.W. (2000). Computing and computer modelling in Geotechnical Engineering. Proceedings of ISRM International Symposium, 1, pp. 1157-1252, ISRM, Melbourne, Australia.

Lemos, C.C.D.S., Dias, L.O.F., Barbosa, P.S.D.A., Marques, E.A.G., Ferraz, R.L. Nalon, G.H. (2024). Digital tools used on the teaching-learning process in geotechnical engineering. *Soils and Rocks*, 47(2), p.e2024004923. doi: 10.28927/SR.2024.004923

Pinho-Lopes, M. (2012). Implementation of the use of computing and software in undergraduate Soil Mechanics courses. Proceedings of Geotechnical Engineering Education, Pantazidou, M., Phillips, A. (Eds.), pp. 193-200, Taylor & Francis Group, Galway, Ireland.

Rose, L.M. (1978). The Introduction of Engineering Students to Engineering Design Computer Packages. *European Journal of Engineering Education*. 3(4), pp. 233-237. doi: 10.1080/03043797808548460

Rothberg, S. J., Lamb, F. M., Willis, L. (2006). Computer assisted learning in UK engineering degree programmes: lessons learned from an extensive case study programme. *Eur. J. of Engineering Education*, 31(4), pp. 395- 406. doi: 10.1080/03043790600676174

Taborda, D.M.G., Kontoe, S., Tsiampousi, A. (2024). IC MAGE Model 01 – strain-hardening/softening Mohr-Coulomb failure criterion with isotropic small strain stiffness (Version 2.2). Zenodo. doi: 10.5281/zenodo.13891265

Taborda, D.M.G., Kontoe, S., Tsiampousi, A. (2024). IC MAGE UMIP – universal model interface for PLAXIS (Version 3.6). Zenodo. doi: 10.5281/zenodo.13890543

Tsiampousi, A, Kontoe, S, Taborda, DMG (2024). IC MAGE Model 06 – Modified Cam-clay model with a non-linear Hvorslev surface and isotropic non-linear stiffness (Version 1.7). Zenodo. doi: 10.5281/zenodo.14369564

Vairaktaris, E., Metaxas, G., Damigou, D. (2008). Contribution of numerical methods in the education of geosciences: Implementation on two-tier study programs. Proceedings of Education and Training in Geo-Engineering Sciences. Manoliu, I., Radulescu, N. (Eds) p.337-344. CRC Press, Constanza, Romania. doi: 10.1201/9781482266436

Zoghi, M. (1996). Use of personal computers to enhance the geotechnical engineering education. Proceedings of American Society of Engineering Education (ASEE) Annual Conference. 1, pp. 499.1-499.4, Washington, USA. doi: 10.18260/1-2--6367

Authors' bios

Aikaterini Tsiampousi, Imperial College London (United Kingdom)

Dr Aikaterini Tsiampousi is a Senior Lecturer in Geotechnics in the Department of Civil and Environmental Engineering at Imperial College London. She studied Civil Engineering in Aristotle University of Thessaloniki, Greece, and has a MSc in Soil Mechanics and a PhD in Geotechnical Engineering from Imperial College London. Her research focuses on the development and application of numerical tools to study the behaviour of geotechnical infrastructure under various loading conditions, including soil-atmosphere interactions. She was the Course Director of the MSc in Soil Mechanics from 2020 to 2022 and is currently Director of Post-Graduate Taught Programmes, developing the strategy and curricula of six MSc programmes in the Department and their options and interactions. Her personal teaching spans numerical analysis at Undergraduate and Postgraduate levels, geotechnical infrastructure, and design and research projects.

Pishun Tantivangphaisal, Imperial College London (United Kingdom)

Pishun Tantivangphaisal is a final year PhD student in the Geotechnics section in the Department of Civil and Environmental Engineering. His research interest spans the development, implementation and practical use of computational methods in geotechnics, as well as the translation of academic research into real engineering practice. He actively bridges these two realms through his current role as the Academic Liaison on the Early Careers Offshore Site Investigation and Geosciences Committee, and former committee roles with the British Geotechnical Association Early Career Group. Over the past three years, he has led the team of graduate teaching assistants in delivering the practical aspects of the presented Applied Numerical Analysis module. In his role as a consulting geotechnical engineer at Arup, he regularly contributed to a monthly "soil mechanics club" to upskill other graduate engineers by revisiting fundamental theory in the context of real engineering projects.

Initial study on leveraging digital tools for geotechnical education: enhancing practical training with databases at CiviLab@CUT

S.G. Waters & E. Theron

Central University of Technology, Free State, South Africa
swaters@cut.ac.za, etheron@cut.ac.za

ABSTRACT: This study explores the development and implementation of the Information System for Geotechnical Engineers (ISGE) at CiviLab@CUT, aimed at improving geotechnical education through digital data management. The ISGE integrates a cloud-based relational database (PostgreSQL, AcuGIS) with automated data validation and error detection, ensuring compliance with SANS 3001 standards. Traditionally, students relied on manual data entry, leading to errors and limited iterative learning. The ISGE addresses these issues by implementing structured validation, automated feedback, and comparative analysis, enabling students to refine testing accuracy. A comparative analysis of historical and newly collected student test data was conducted using statistical methods such as mean absolute error, and standard deviation. Preliminary findings indicate a reduction in data entry errors, improved test result consistency, and enhanced student engagement. The ISGE also supports scalability, with potential expansion into a national geotechnical database to improve data-driven decision-making. By integrating digital tools into practical training, the ISGE enhances geotechnical education, fosters data standardization, and better prepares students for industry challenges through iterative assessment.

Keywords: *Geotechnical engineering, Information system, Data management, Integrated student education*

1 Introduction

1.1 Background on geotechnical engineering education in the Central University of Technology, Free State

Geotechnical engineering is a fundamental aspect of infrastructure development, ensuring the stability and suitability of soil and rock for construction. In South Africa, laboratory testing in geotechnical engineering is governed by the SANS3001 standards. These standards define procedures for assessing soil properties and material behaviour and are essential for maintaining consistency and reliability in geotechnical investigations and construction practices. The geotechnical characteristics of a site play a crucial role in all phases of construction, from planning and design to implementation and long-term stability. Soil and rock conditions significantly influence construction feasibility, foundation design, and structural integrity. (De, 2015) Neglecting geotechnical assessments can lead to costly failures, as evidenced by numerous international case studies highlighting the impact of inadequate geotechnical considerations on construction projects (Tegtmeier et al., 2009). Ensuring future engineers understand soil assessment through laboratory testing is vital for safer geotechnical design and construction (Coduto et al., 2016). This paper explores how the ISGE system not only minimizes experimental errors but also actively promotes critical thinking and engineering judgment among geotechnical engineering students. By integrating structured feedback mechanisms, comparative analysis tools, and scaffolded learning approaches, the ISGE system serves as a pedagogical tool that enhances students' analytical skills and decision-making capabilities.

CiviLab@CUT, a research group within the Department of Civil Engineering at the Central University of Technology, offers comprehensive training to students through two primary avenues: structured coursework and volunteer-based programs. These initiatives are designed to equip students with both theoretical knowledge and practical skills in geotechnical engineering.

In the structured academic programs, students enrol in courses such as Soil Mechanics I (Diploma level) and Geotechnical Engineering I (Bachelor's degree level). These courses include five practical sessions per semester, where students are assessed on their proficiency in conducting standard geotechnical tests and analyzing the resulting data. Data processing is performed manually or with the assistance of Microsoft Excel, ensuring that students develop a solid understanding of fundamental calculations and data interpretation techniques.

Beyond formal coursework, CiviLab@CUT provides hands-on training opportunities through volunteer programs, work-integrated learning (WIL), and research assistantships. Participants in these programs engage in regular geotechnical testing, gaining exposure to real-world applications and reinforcing data consistency through repeated practice. These experiences encompass the full spectrum of geotechnical workflows, from field assessments of test pits to laboratory analyses of collected samples. Typically spanning one year, these programs are instrumental in developing students' technical competencies and analytical abilities essential for professional practice.

A common challenge observed across these training modalities is the initial variability in test results, often attributed to students' limited experience. While performance tends to improve with practice, the substantial volume of data generated poses difficulties in individualized assessment and feedback. In undergraduate courses, the singular assessment per practical session restricts opportunities for iterative learning and skill refinement. Conversely, WIL participants, despite their frequent testing activities, often lack structured expert evaluations, leading to inconsistencies in quality control and missed learning opportunities.

1. To address these challenges, the Information System for Geotechnical Engineering (ISGE) has been implemented as an integral component of both educational tracks. The ISGE system introduces structured feedback mechanisms that enhance learning outcomes by:
2. Immediate Error Detection: The system flags discrepancies in test results, such as significant deviations in liquid limit measurements, prompting students to reassess their methodologies and calculations.
3. Guided Reflection: Upon identifying errors, students are required to document corrective actions and rationalize their decisions, fostering critical thinking and aligning with professional engineering practices.
4. Comparative Analysis: By providing access to historical data, the ISGE system enables students to discern patterns, differentiate between procedural errors and natural soil variability, and develop informed engineering judgments.
5. Scaffolded Skill Development: The system supports novice learners by offering structured guidance, while gradually encouraging autonomy as students gain proficiency, thus balancing automated assistance with the cultivation of independent analytical skills.

The integration of the ISGE system into CiviLab@CUT's training programs has proven effective in enhancing the quality and consistency of geotechnical education. By facilitating iterative learning, promoting critical analysis, and providing a platform for comprehensive feedback, the ISGE system ensures that students are better prepared to meet the demands of professional geotechnical engineering practice.

1.2 The information system for geotechnical engineers (ISGE)

The Information System for Geotechnical Engineers (ISGE) was developed in the CiviLab@CUT to address challenges in geotechnical data management, accessibility, and decision-making in South Africa. Traditional geotechnical practices often relied on paper records and scattered Microsoft Excel files, leading to inefficiencies, data loss, and restricted access to critical test results. The ISGE provides a centralized system designed to improve the storage, retrieval, and analysis of geotechnical test data. It also ensures compliance with SANS3001 standards and supports more informed engineering decisions.

One of the primary motivations behind the ISGE was to enhance the desktop study phase of site investigations. Desktop studies serve as preliminary assessments before detailed geotechnical

investigations and involve reviewing topographical maps, historical geotechnical data, and geological information to identify potential risks. In South Africa, access to past geotechnical data is often limited, making site feasibility assessments difficult. The ISGE was developed as a database-driven system to overcome these limitations by structuring geotechnical test results into an accessible and standardized format.

The ISGE was designed to bridge the gap between academic research and industry application. Developed by CiviLab@CUT, the system provides students, volunteers, and industry professionals with a structured platform for storing, retrieving, and comparing geotechnical test results. By improving data consistency and accessibility, the ISGE enhances long-term knowledge retention and supports better decision-making in geotechnical investigations.

Scalability was a key consideration in the development of the ISGE. The system is designed to evolve into a national geotechnical database, where engineers across South Africa can contribute and access historical soil test data. This broader integration could significantly improve regional geotechnical analysis, infrastructure planning, risk assessment, and research applications.

The ISGE was, therefore, integrated into undergraduate coursework, volunteer training programs, and work-integrated learning (WIL), for this study to evaluate the potential impact of the ISGE on student performance over time, examining its role in improving accuracy, efficiency, and the interpretation of geotechnical data.

2 Literature review

2.1 Importance of geotechnical testing

Geotechnical engineering, a sub-discipline of civil engineering, focuses on understanding the physical properties of soil and rock to ensure the stability of structures. Soil mechanics, as a key component, examines soil behaviour under various forces, making geotechnical investigations crucial for construction planning and design (Das, 2013; Waters, 2022). Site investigations typically involve a combination of desktop studies, field tests, and laboratory analyses. The desktop study includes a review of geological and topographical maps, while fieldwork consists of test pits, boreholes, and soil sampling. Laboratory tests, which form the core of geotechnical evaluations, provide detailed information on soil composition, strength, and behaviour under different conditions (Craig, 2005; SANRAL, 2013). Performance-based tests, including California Bearing Ratio (CBR), direct shear, triaxial shear, and one-dimensional consolidation tests, further aid in categorizing soils and predicting their response to loading.

2.2 Standardized geotechnical testing methods

Geotechnical engineering relies on standardized testing to ensure consistency and reliability in soil characterization. In South Africa, the SANS 3001 series govern civil engineering test methods, having replaced the older TMH1 standards to align with international best practices (South African National Roads Agency, 2013; SABS, 2013). These standards define procedures for essential tests such as Atterberg limits, CBR, and consolidation testing, providing a framework for assessing soil behaviour under various loading conditions (Das, 2013; Craig, 2004). However, despite their technical rigor, practical challenges arise in educational settings. Students often face difficulties with procedural complexities and the variability of soil data (Waters, 2022). Errors in data entry, inconsistent execution, and limited feedback opportunities reduce the pedagogical effectiveness of traditional lab instruction (Viljoen, 2006), highlighting the need for enhanced support systems that maintain standards compliance while facilitating student learning.

2.3 Laboratory learning in geotechnical education

Laboratory testing is central to soil mechanics education, offering students hands-on opportunities to bridge theory and practice (Feisel & Rosa, 2005). Effective laboratory experiences promote technical proficiency and engineering judgment, especially when students are encouraged to interpret their own results and confront uncertainties (Kolb, 1984). Yet, without structured guidance, laboratory sessions may result in surface-level learning where procedural completion takes precedence over conceptual

understanding (Domin, 1999). To foster critical thinking and reflective analysis, laboratories must be intentionally designed to develop interpretive skills and empirical reasoning.

2.4 Formative Assessment and Digital Tools in Engineering Education

Modern engineering education increasingly emphasizes formative feedback and iterative learning as essential for developing technical competence and critical thinking. Studies show that formative assessments with opportunities for repeated practice enhance engagement and lead to mastery in engineering contexts (Burns et al., 2023; Ramesh et al., 2023). Technology-enhanced learning environments that offer immediate, multiple-attempt feedback reduce student stress and promote inclusive, equitable learning experiences. Furthermore, integrating digital tools into practical education supports scaffolded and mastery-based learning, encouraging students to take ownership of their development (Diery et al., 2024). Systems like ISGE exemplify this shift by embedding real-time validation, comparative analysis, and reflective activities into student workflows—bridging the gap between theoretical knowledge and applied engineering judgment.

2.5 Educational role of validation and standardization systems

Recent studies in STEM education have explored the role of validation systems that highlight incorrect data inputs or flag inconsistencies (Formanek et al., 2021; Daheim et al., 2024). While there is concern that students may become dependent on such systems, research suggests that when used alongside reflective activities and instructor guidance, automated checks can actually increase awareness of errors and lead to improved understanding over time (Van der Kleij et al., 2015; López-Crespo et al., 2022). In geotechnical engineering, where data scatter and procedural inconsistency are common among novices, structured systems can reinforce standard practices and help students differentiate between material variability and methodological error.

2.6 Information systems and databases

An information system is a software framework designed for storing, organizing, and retrieving data. In geotechnical engineering, such a system must facilitate structured data management, integrating various test results to assist engineers in decision-making. The Information System for Geotechnical Engineers (ISGE) follows this principle, ensuring accessibility, comparability of historical and current data, and standardization of test results (Ramesh, 1997). A user-friendly interface for transforming raw test readings into meaningful information is essential, aligning with SAICE Code of Practice for geotechnical investigations. The ISGE is designed to be scalable and adaptable, allowing expansion to incorporate future geotechnical tests and database enhancements (Viljoen, 2006).

A database is a structured collection of data stored and accessed electronically, managed by a Database Management System (DBMS). Proper database design is crucial to ensure data integrity, accessibility, and efficient decision-making. Raw data, when processed, becomes meaningful information, forming the foundation for informed engineering decisions. A Relational Database Management System (RDBMS) organizes data into tables (relations), where rows (records) store individual entries and columns (fields) represent attributes. A primary key uniquely identifies each record, ensuring referential integrity between tables (Satzinger et al., 2012).

A key feature in relational databases is normalization, a formal process used to reduce redundancy and enhance flexibility. By structuring data correctly, normalization ensures that databases remain scalable and adaptable to future changes. The ISGE employs these principles to provide a dynamic, real-time geotechnical data management system, supporting standardized reporting, historical data comparisons, and streamlined decision-making in South African geotechnical engineering.

3 Methodology

This study employs a structured approach to enhancing and evaluating the effectiveness of the Information System for Geotechnical Engineers (ISGE) in geotechnical education. The methodology consists of two primary phases: system improvements and student engagement, which will be followed by comparative analysis of student results over time. The first phase focused on refining the ISGE by

implementing automated data validation checks, error detection mechanisms, and comparative data analysis. These improvements ensured that student-entered data adhered to predefined thresholds and SANS3001 standards. The system was also designed to store, retrieve, and compare test results through queries made via the Open Database Connectivity (ODBC).

Following these modifications, students are granted limited user access to the ISGE database to input test results. This phase allowed students to engage with the database, ensuring they followed structured data entry procedures while integrating their test results into the system.

The ISGE system is designed to complement traditional soil mechanics education by integrating structured feedback loops that promote deeper understanding. Key features include:

1. Collecting historical test results from past student groups in Geotechnical Engineering I and Soil Mechanics I for Atterberg limits (Practical 2 in course). Each class had between 60 and 120 students per semester. Previous results of WIL students and volunteers (estimate of 50 students) will be imported into the database.
2. Recording new student test results obtained through the ISGE.
 - Students conduct the Casagrande cup test to determine liquid and plastic limits.
 - Students input their results into Excel sheets, which perform preliminary validation. The system flags significant discrepancies, such as liquid limit variations exceeding 7% or incorrect relationships (e.g., a plastic limit higher than the liquid limit).
 - Results are stored in the ISGE database, with student-entered data tagged separately to prevent its use in industry applications.
 - Server-based SQL scripts and Excel calculations analyze all submitted results, generating standard deviations, ANOVA tests, and distribution curves. The system also cross-references results against other tests from the same sample to verify consistency.
3. Structured course students receive direct feedback from lecturers or mentors, while experienced volunteers can review system-generated assessments to identify and correct errors in their results. Comparing accuracy trends by analyzing variations in test results, identifying improvements, and assessing whether error rates decreased over time.

Figure 1 demonstrates the discussed approach for using the ISGE system for enhancing geotechnical education through a structured, data-driven approach. The collection of results will be an iterated cycle of assessing the student results and provision of feedback through lecturers or self-assessment.

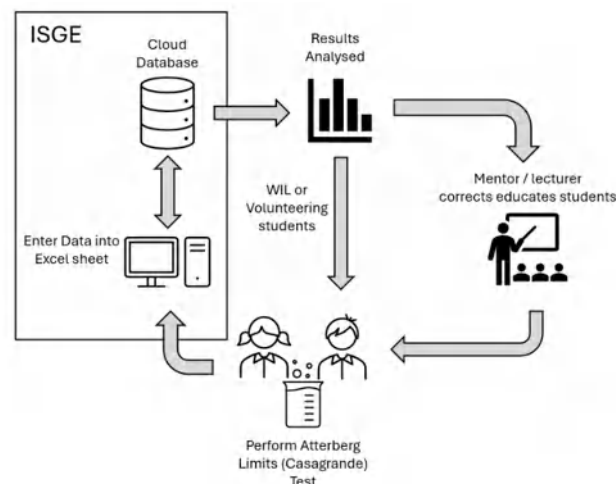


Figure 1. Process of assessing results

The ISGE system was not designed merely to reduce error rates, but to serve as a scaffold that promotes deeper learning and the development of engineering judgement. In traditional laboratory settings, students often receive minimal feedback on their results and have limited opportunity to revise or question flawed outcomes. As a result, learning is often procedural, with students prioritizing test completion over understanding variability or identifying test anomalies.

By integrating real-time validation checks and structured feedback based on SANS 3001 standards, the ISGE shifts the focus from compliance to reflection. When students receive automated warnings about

implausible results (e.g., plasticity index inconsistencies), they are prompted to critically examine their procedures, materials, and assumptions. Rather than simply accepting system-generated warnings, students are encouraged to interpret them, reflect on potential sources of error, and revise their approach. In this way, the system acts as a diagnostic guide, not a prescriptive authority.

Furthermore, students are not penalized for submitting flawed results; instead, instructors emphasize that flagged results are learning opportunities. During laboratory follow-up sessions, students are asked to justify their choices, discuss flagged anomalies, and identify whether discrepancies stemmed from procedural mistakes, equipment limits, or natural soil variability. This process cultivates data literacy, reinforces standard compliance, and helps students distinguish between random variation and methodological error—key components of geotechnical competence.

For WIL and volunteer students, the ISGE serves as a tool for independent self-regulation. Over time, trainees develop an internalized sense of data quality and procedural rigour, with the system providing structure but not dependency. Monthly feedback sessions reinforce this autonomy, with students presenting and interpreting their own performance trends using the system's analytics.

3.1 Fostering Critical Thinking Through Iterative Feedback

Early implementation has shown measurable impact. For example, students now receive immediate feedback when entering data that violates standard thresholds. This has led to a marked reduction in erroneous submissions. Students are also more reluctant to submit incomplete or invalid results — a shift attributed to the system's feedback mechanisms, which highlight errors and explain their likely causes. This change has led to a lower volume of submitted data, but with significantly improved reliability.

Additionally, the ISGE's ability to consolidate results into a standardized format has supported both teaching and mentoring. Structured feedback, either through the system or from instructors, is now directly tied to student entries, reinforcing correct procedures and helping students correct misunderstandings. The system's alignment with real-world data practices has also encouraged greater student ownership of the results they produce. The structure of the ISGE is shown in Figure 2.

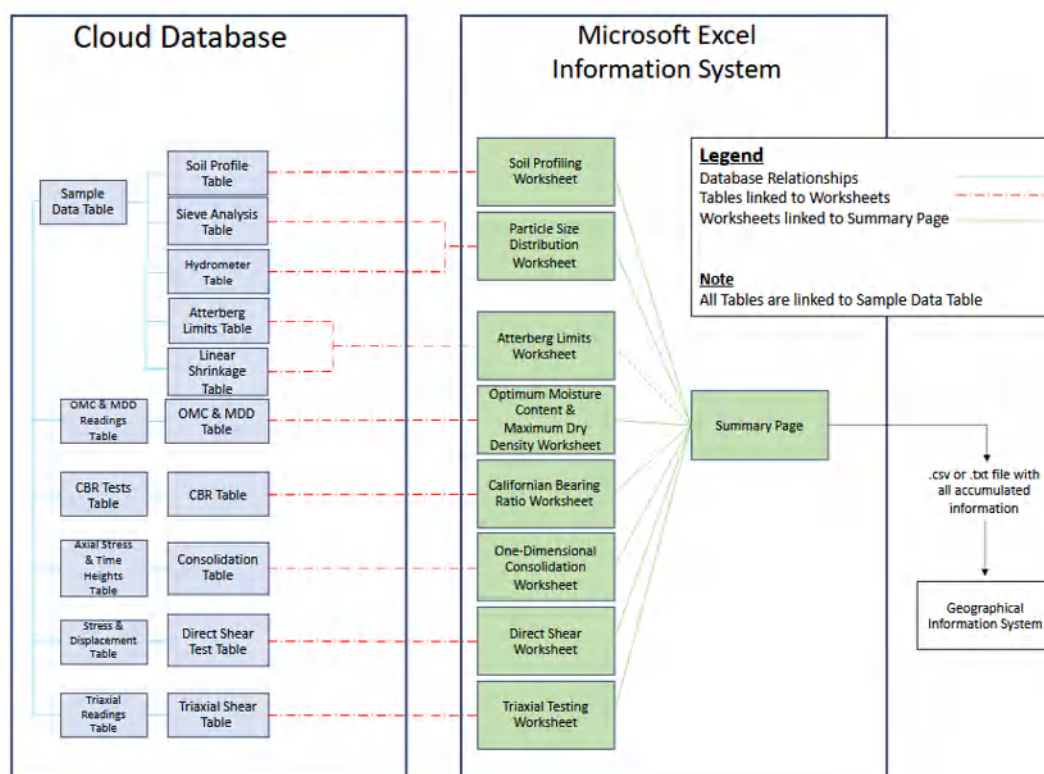


Figure 2. Layout of ISGE system

3.2 Database design and implementation

The database for the (ISGE) was developed to provide a structured approach to storing and managing geotechnical data. The design follows a relational database model, ensuring efficient data organization, integrity, and accessibility. Microsoft Access was initially chosen as the primary database platform due to its ease of use and seamless integration with Microsoft Excel, which was used for advanced calculations, visualization, and automated reporting. However, the database has now been uploaded to a cloud-based storage (AcuGIS, PostgreSQL) to allow better sharing capabilities and collaborative access among users. The transition to AcuGIS with PostgreSQL enhances the system's scalability, allowing multiple users to input, retrieve, and analyze geotechnical data simultaneously from across the country (keeping scalability in mind). This cloud-based solution improves data security, backup reliability, and accessibility, ensuring that test results and site investigation records are preserved without risk of local storage failures.

The database structure consists of multiple tables, each representing a specific geotechnical test such as particle size distribution, Atterberg limits, California Bearing Ratio (CBR), and one-dimensional consolidation tests. A primary table stores essential sample data, linking all other tables through one-to-many relationships, ensuring each test result is associated with a unique sample identification ("sample_id"). This relational structure prevents data redundancy, enhances data integrity, and enables efficient queries.

To facilitate data retrieval and analysis, queries were created to aggregate data from multiple tables. These queries provide engineers and students with structured test results, enabling effective comparison of historical and current data. The summary page interface within the ISGE compiles geotechnical test results, providing a clear overview of key parameters.

One of the critical components of the database design was ensuring compliance with SANS3001 standards, which regulate geotechnical testing in South Africa. The database structure allows for the storage and manipulation of geotechnical test data according to these standards, ensuring consistency and regulatory adherence.

4 Modifications to the ISGE for assessing geotechnical test results

A crucial modification was the implementation of automated feedback and quality control measures to assess student and engineer-entered test results. These mechanisms detect potential errors, flag anomalies, and verify compliance with SANS3001. The error-checking functionality automatically compares input values against predefined threshold ranges. For example, Atterberg limit test results are assessed based on standard plasticity index ranges, while CBR test results are checked against expected strength values. If discrepancies arise, the system highlights outliers and prompts users to review the data, minimizing inaccuracies in geotechnical reporting.

Beyond direct error detection, the ISGE includes statistical analysis tools that compare historical test results with new data, allowing users to determine whether variations are due to soil heterogeneity or potential testing errors. This feature is particularly valuable for long-term site monitoring and research applications, where consistency in geotechnical properties must be tracked over time. The summary page interface plays a central role in quality control by consolidating all test results into a standardized report format, ensuring clarity in geotechnical assessments. Additionally, the system can generate SANS3001-compliant test reports, ensuring that all documentation meets regulatory standards. The ISGE improves geotechnical test assessment by integrating automated validation (as shown in Figure 3), statistical analysis, and cloud-based accessibility. These modifications enhance the accuracy of student test results, minimising human error through correcting the results obtained, and improving the overall reliability of geotechnical investigations in South Africa.

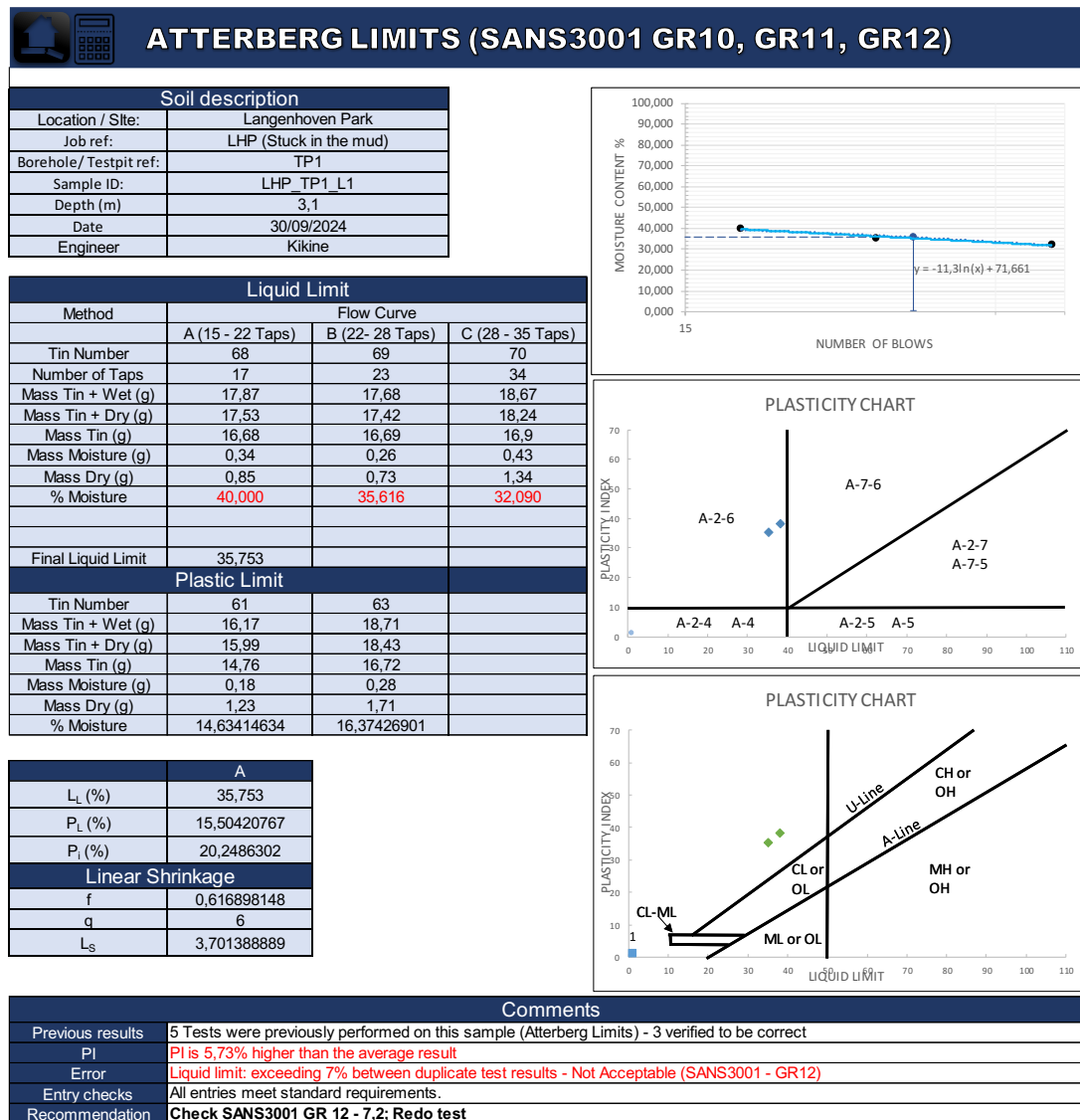


Figure 3. Example of data verification and comparison in Atterberg Limit data entry sheet

This sheet automates the initial assessment of results in compliance with SANS 3001 regulations, preventing invalid data from being entered into the database. Figure 3 illustrates a case where the difference between data points exceeds 7%, triggering an assessment of input validity. The system also references the relevant standards, providing students with targeted feedback to identify and correct errors.

4.1 Comparative analysis of learner test results

Preliminary observations indicate that the ISGE has already led to noticeable improvements in student data quality and engagement. The system's built-in validation checks prevent the submission of incomplete or implausible results, leading to a sharp reduction in the number of invalid test entries. For example, students are no longer able to proceed with uploading Atterberg limit data that violates fundamental consistency rules, such as a plastic limit higher than the liquid limit or a liquid limit variation exceeding 7%. These technical constraints have translated into a significant behavioural shift: students are now more cautious and deliberate when conducting tests and entering data, often opting to repeat a test rather than submit flagged results.

This behaviour reflects a growing awareness of quality standards and a greater alignment with professional geotechnical practices. It also suggests that students are engaging in more iterative learning — revisiting procedures, questioning anomalous results, and seeking clarification from mentors. This aligns with one of the core goals of the ISGE: to promote reflective, standards-based practice that mirrors real-world engineering environments.

While full statistical analysis is still ongoing, early trends are promising. The initial datasets show narrower standard deviations in student test results compared to historical data, suggesting improved consistency. A decline in data variability is particularly evident among Work-Integrated Learning (WIL) students, who are now using ISGE for extended periods across multiple testing sessions. As the dataset grows throughout 2025, the system will support more robust statistical analysis using descriptive metrics such as mean absolute error (MAE), standard deviation, and linear regression trends to track improvement trajectories.

Importantly, the ISGE tags student-entered results distinctly from professional datasets, allowing for safe inclusion in the learning environment without compromising industry reporting. This dual-purpose design enhances student accountability while ensuring educational use remains clearly separated from operational applications.

While the initial implementation of ISGE led to a decrease in the number of test results submitted, this was not due to grade anxiety or fear of penalties. Students were explicitly informed that flagged data would not negatively affect their marks and that the system was designed as a formative learning tool. The observed decrease instead reflects a shift in student behaviour: many chose to repeat tests when inconsistencies were highlighted, seeking to produce more accurate results. Informal feedback and classroom discussions revealed that students became more aware of procedural accuracy and expressed increased confidence in interpreting standards-based results. In future iterations, students will be encouraged to submit flawed results alongside written reflections, enabling deeper insight into their understanding and decision-making process. This reflective submission strategy will ensure that hesitation to submit does not inhibit learning but becomes an opportunity for metacognitive development.

5 Conclusions and future work

The implementation of the Information System for Geotechnical Engineers (ISGE) at CiviLab@CUT marks a meaningful advancement in geotechnical education. By combining a cloud-based relational database (PostgreSQL, AcuGIS) with structured validation and feedback mechanisms, the ISGE directly addresses key challenges of data accuracy, management, and standardization in student laboratory work.

Early results indicate a clear reduction in submission errors, greater consistency in student test data, and a shift in behaviour toward more reflective, standards-driven testing practices. These outcomes suggest that the system not only improves the reliability of practical assessments but also supports iterative learning through immediate, targeted feedback. Importantly, the integration of SANS 3001 compliance into the learning process reinforces industry-aligned procedures from the outset.

As data collection continues throughout 2025, further analysis will be used to quantify long-term improvements in student performance and evaluate broader educational outcomes. Future work will focus on expanding ISGE's statistical and reporting capabilities, investigating industry integration, and exploring the feasibility of a national geotechnical database to enhance collaboration and data reuse across South Africa.

By embedding regulatory standards into student workflows and offering structured feedback, the ISGE establishes a scalable model for bridging the gap between academic training and professional geotechnical practice. It provides a foundation not only for better student outcomes, but also for a more data-driven, standardized approach to geotechnical testing nationwide.

References

- Bollin, A., et al. (2023). Learning Software Project Management by Simulation', Proceedings of the SEFI Conference 2023.
- Burns, M.A., Johnson, V.N., Grasman, K., Habibi, S., Smith, K.A., Kaehr, A., Lacar, M.F., Yam, B. (2023). Pedagogically grounded techniques and technologies for enhancing student learning. *Advances in Engineering Education*, 11(3).
- Casagrande, A. (1932). Research of Atterberg limits of soils. *Journal of the Soil Mechanics and Foundations Division, ASCE*, 13, pp. 121–136.

- Coduto, D.P., Yeung, M.R., Kitch, W.A. (2016). *Principles of Geotechnical Engineering*. Stamford: Cengage Learning.
- Craig, R.F. (2005). *Craig's Soil Mechanics*, 7th edn. London: Spon Press (Taylor & Francis Group).
- Daheim, N., Macina, J., Kapur, M., Gurevych, I., Sachan, M. (2024). Stepwise verification and remediation of student reasoning errors with large language model tutors. *Proceedings of the 2024 Conference on Empirical Methods in Natural Language Processing (EMNLP 2024)*, pp. 9876–9890. Available at: <https://aclanthology.org/2024.emnlp-main.478.pdf> (Accessed: 5 May 2025).
- Das, B.M. (2013). *Principles of Geotechnical Engineering*, 8th edn. Stamford: Cengage Learning.
- Das, S. (2017). *Principles of Geotechnical Engineering*, 9th edn. Boston: Cengage Learning.
- De, A. (2015). *Geotechnical Site Characterization*. New York: Momentum Press.
- Diery, D., Caratozzolo, M., Armstrong, J. (2024). Future skills for Industry 4.0 integration and innovative learning for continuing engineering education. *Frontiers in Education*, 9. Available at: <https://doi.org/10.3389/educ.2024.1412018> (Accessed: 5 May 2025).
- Feisel, L.D., Rosa, A.J. (2005). The role of the laboratory in undergraduate engineering education. *Journal of Engineering Education*, 94(1), pp. 121-130.
- Kolb, D.A. (1984). *Experiential Learning: Experience as the Source of Learning and Development*. Englewood Cliffs: Prentice-Hall.
- López-Crespo, G., Fernández-Fernández, M., García-Carmona, A., Ruiz-Gallardo, J.R. (2022). Design and validation of assessment tools for measuring the impact of STEM informal learning initiatives', *Sustainability*, 14(13), 7831.
- Nicol, D.J., Macfarlane-Dick, D. (2006). Formative assessment and self-regulated learning. *Studies in Higher Education*, 31(2), pp.199-218.
- Ramesh, G. (1997). *Database Management Systems*, 2nd edn. New York: McGraw-Hill.
- Ramesh, G., Jackson, R.B., Burd, S.D. (2023). Encouraging engineering design teams to engage in expert iterative practices. *Journal of Engineering Education*, 112(4), pp. 1012-1031.
- Satzinger, J.W., Jackson, R.B., Burd, S.D. (2012). *Systems Analysis and Design in a Changing World*, 6th edn. Boston: Cengage Learning.
- South African Bureau of Standards (SABS) (2013). *SANS 3001: Civil Engineering Test Methods*. Pretoria: SABS.
- South African Institution of Civil Engineering (SAICE) (2010). *Site Investigation Code of Practice*. South Africa: The Geotechnical Division of SAICE.
- South African National Roads Agency (SANRAL) (2013). *Technical Methods for Highways (TMH1) and Transition to SANS 3001*. Pretoria: SANRAL.
- Tegtmeier, W., Zlatanova, S., Oosterom, P.J.M., Hack, R. (2009). 3D geoinformation for geotechnical and geohazard analysis', *Geotechnical and Geological Engineering*, 27(4), pp. 565–577.
- Van der Kleij, F.M., Feskens, R.C.W., Eggen, T.J.H.M. (2015). Effects of feedback in a computer-based learning environment on students' learning outcomes: A meta-analysis. *Review of Educational Research*, 85(4), pp. 475–511.
- Viljoen, A.W. (2006). *Geotechnical Data Management: The Role of Databases in Site Investigations*. Johannesburg: South African Institute of Civil Engineering.
- Waters, S.G. (2022). *Development of an Information System for Geotechnical Engineers Towards Improved Decision Making*, Master's dissertation, Central University of Technology, Free State.
- Weng, J. (2024). *Critical Thinking with AI: Navigating ChatGPT in Engineering Education*. SEFI 2024 Conference Paper.

Authors' bios

Samuel G Waters, Central University of technology, Free State (South Africa)

Samuel Waters is a lecturer in Geomatics and Engineering Surveying at the Central University of Technology, Bloemfontein, with seven years of academic experience. He also teaches the final-year Project subject, integrating practical applications with theoretical knowledge. His research focuses on database design, problematic soil identification, road inspection, and Geographic Information Systems (GIS). He has contributed to the field through publications and conference presentations, with his work recognized by the National Research Foundation of South Africa, which awarded him a Thuthuka Research Grant for 2025. Samuel is committed to advancing geospatial and geotechnical methodologies, particularly in South Africa's diverse soil and infrastructure environments.

Elizabeth Theron, Central University of technology, Free State (South Africa)

Professor Theron has over 35 years of experience in academia, with a strong focus on geotechnical engineering. She has developed innovative teaching materials and methodologies, significantly enhancing student learning experiences. Her research, particularly on foundation problems related to heaving clays, has earned her multiple awards, including the J.E. Jennings Award from the South African Institution of Civil Engineering for three consecutive years (2017-2019). In addition to her academic roles, she actively participates in community projects, such as the Pothole Eradication Programme, demonstrating her commitment to applying engineering solutions to real-world challenges. As a registered Professional Engineering Technologist with the Engineering Council of South Africa, she maintains high professional standards in her work.

Teaching the significance of numerical model validation with problem-based learning: examples from rock mechanics

Paraskevi Yiouta-Mitra

National Technical University of Athens, Greece
antipaxos@metal.ntua.gr

ABSTRACT: Numerical modelling is universally acknowledged as a powerful tool in the hands of engineers. At the same time, it is no secret that inexperienced engineers - either due to youth or due to limited comprehension of the theory behind the finite elements, finite differences, discrete elements and other methods, can also be dangerous and lead to irrational, uneconomical or worse, deadly designs. It is therefore of the utmost importance to train the students in the concepts and methodologies of validating their own models prior to utilizing them for the design of complex structures. The main concept behind any numerical model validation is to start by the simplest setup of the physical problem and build up the complexity as far as analytical solutions exist with which the model results can be verified. Another approach, which is not bound by the existence of an analytical solution, is to verify the results with monitoring data collected during various phases of construction. The advantages and drawbacks of the two approaches are discussed, especially with respect to the ease of implementation in the classroom. The first approach is selected for full demonstration of problem-based learning for a specific chapter in rock mechanics: the behaviour of hard rock mass with ubiquitous joints around a circular tunnel or shaft. The project can be implemented in advanced rock mechanics classes that include numerical analysis and realized with any geotechnical software able to model discontinuities in combination to calculation sheets for the analytical solution.

Keywords: *Model validation, Ubiquitous joints, Analytical solution, Numerical simulation, Rock mechanics education*

1 Introduction

The merits of numerical modelling and the wide implementation of the numerical approach for the design of engineering structures are undeniable. It is therefore reasonable to expect that engineering education devotes a special chapter in teaching the significance as well as the methodology of numerical model validation. The topic is quite fundamental for modern engineering and, in the author's opinion, could be compulsory in engineering curricula. Combined with recent educational strategies, such as project-based learning or flipped classroom teaching, it could become one of the highlights of any geotechnical engineering course. Besides, the specific topic could not easily become part of a traditional test-centric course because it requires coding skills that are developed and demonstrated better in a computer laboratory rather than on a piece of paper or whiteboard. As an integral part of engineering skills, numerical model validation is hereby proposed to be taught through a post-modern educating view of teamwork, interdisciplinary competence and dialogical practice for decision-making.

Problem-based learning (PBL) is a process that is used to identify problems with a scenario to increase the knowledge and understanding (Barrows, 1998; Akinoğlu et al., 2007; Ali, 2019). Some of the principles include: (i) Independent and self-directed learning; (ii) Learning happens in a group and the teacher is a facilitator; (iii) All groups must participate equally; (iv) Students learn about motivation, teamwork, problem-solving and engagement through the task; (v) Materials such as data, photographs, articles, can be used to solve the problem.

A well-designed PBL project provides students with the opportunity to develop significant skills. Learning outcomes of higher levels are formulated. In Bloom's taxonomy of learning objectives the levels reached through PBL start at level 3 and are: 3 – Apply, 4 – Analyse, 5 – Synthesize/Evaluate, and 6 – Create. Nilson (2010) lists the following skills that are associated with PBL: (i) Working in teams; (ii) Managing projects and holding leadership roles; (iii) Oral and written communication; (iv) Self-awareness and evaluation of group processes; (v) Working independently; (vi) Critical thinking and analysis; (vii) Explaining concepts; (viii) Self-directed learning; (ix) Applying course content to real-world examples; (x) Researching and information literacy; (xi) Problem solving across disciplines.

Problem-based learning can be combined to project-based learning by shifting the focus to the final product. Students, as individuals or in groups, apply course knowledge to produce a report, written or oral, a process or product design, research or program proposal, or computer code; the procedure is often paired with cooperative learning.

The object of this paper is teaching numerical model validation with modern techniques such as combinations of problem and project-based learning. The examples are sourced from intermediate and advanced rock mechanics subjects suitable for undergraduate and post-graduate levels respectively. The topic is currently included in undergraduate and post-graduate specialized courses on support of underground works. The methodology, however, is universal and may be applied to any scientific field that relies on numerical modelling.

2 Basic concepts

2.1 Principles of numerical model validation and learning model

The main concept behind any numerical model validation is to start by the simplest setup of the physical problem under scrutiny and build up the complexity to the limiting point set by existing analytical solutions. Alternatively, with less limiting conditions, complexity can be built up to the point where monitoring or experimental data have been collected during various phases of the process being modelled. Then, the validation is performed against the monitoring data. In both cases, the entire procedure may be considered as a project assignment to be completed over a specific timeframe.

The time frame is set according to the level of studies and the corresponding complexity of the physical problem that will be modelled. The basic steps relating to learning objectives compose the learning model proposed:

- I. Theory and analytical solution. The learning objective is the identification of the problem and the application of the existing analytical solution. This section employs techniques both traditional, such as lecturing and the use of presentation slides, as well as modern ones, such as flipped classroom, to achieve the learning objectives.
- II. Introduction to numerical methods. This section will not be developed as it is large enough to constitute the object of a separate paper.
- III. Numerical solution. This section is based entirely on modern teaching techniques such as Personal Computer Laboratory (PCLab) hands-on training and PBL and constitutes the main focus of this paper.
- IV. Class presentation and discussion. This section includes reflection that follows the problem-solving work. It is preferred to have it in a group discussion. The purpose of reflection is to make the learning processes and problem-solving skills a daily routine.

If the alternative of monitoring or experimental data is used, then the first step changes to Theory and empirical solution. A proposed model of the topic development is illustrated in Figure 1.

The sequence of the first two steps can differ, so long as the numerical solution is always third in line. The duration for the achievement of each learning objective can vary from 2 to 10 hours, not including out-of-class workload. The "inverse" overall project duration is the intensity of learning. The number of students should be limited to a maximum of 20-25 per teacher, for obvious functional and pedagogical reasons. The Tunnelling Laboratory of the National Technical University of Athens has implemented this learning plan in two courses on Support of Underground Works, taught during the 8th semester for the "Mining Engineering" (integrated) Master's degree (5 years, i.e. 10 semesters), as well as in the post-graduate Specialization Master's degree "Design and Construction of Underground Works".

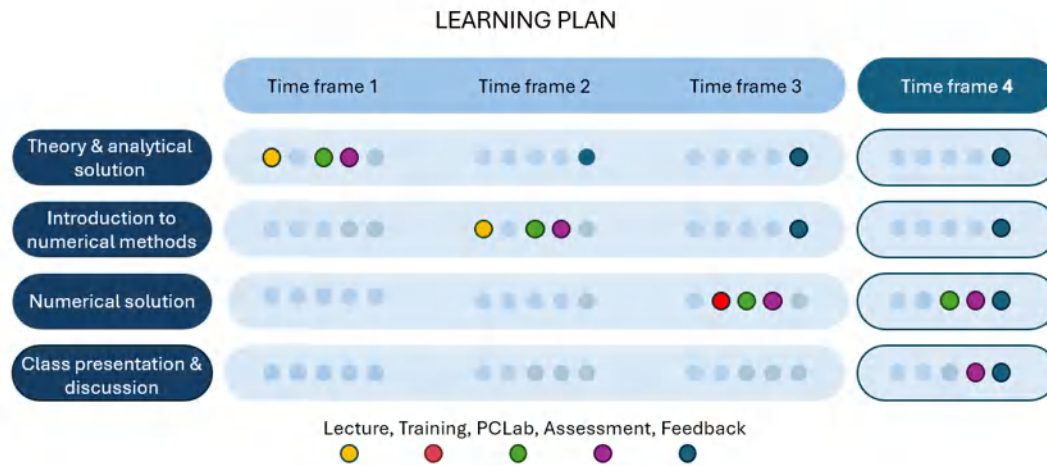


Figure 1. Indicative learning plan for the topic “Numerical Model Validation”

2.2 Rock mechanics topic selected

The selected rock mechanics topic that is used in this paper concerns the instabilities developed in underground excavations due to the presence of weakness planes parallel or nearly parallel to the long axis of the excavation. It can be examined in classroom graphically, analytically and numerically. Especially the numerical methodology, which is targeted in this paper, can be applied a) as continuum analyses by implementing a ubiquitous-joint model as well as b) the more rigorous discontinuum element modelling techniques.

2.3 Theory and background

Competent stratified rockmass is the main geological field of application. Its formation is closely related to sedimentation or metamorphism. The main geometric characteristics of the stratification or schistosity is the planar weakness surfaces and their persistence. Their extent can be considered as surpassing the size of the geotechnical structure in a worst-case scenario. Their mechanical properties are considered to include very low to no tensile strength in the normal to the plane direction and shear strength generally lower than that of the massive rock around them. A wide range of mechanical properties values are possible. Table 1 contains example values for a Mohr-Coulomb strength criterion. It is important to make the distinction between rock properties and discontinuities' properties. The engineering behaviour of rock structures is influenced by discontinuity properties such as frequency, continuity, spacing, roughness, type and degree of infilling, moisture conditions, degree of weathering, mechanical properties (shear strength and deformability), hydraulic properties (permeability or conductivity) and orientation. Therefore, a significant clarification involves the intact rock peak strength and if it is reached before or after the shear peak strength of the discontinuity is surpassed.

Table 1. Indicative range of mechanical properties values

	Cohesion (MPa)	Friction angle (°)	Elasticity modulus (GPa)	Poisson's ratio (-)	Tensile strength (MPa)	Normal stiffness (GPa/m)	Shear stiffness (GPa/m)
Rock	1-4	30-50	30-50	0.3	0.5-4	-	-
Joint	0.005-0.5	12-30	-	-	-	10-1000	1-100

Underground civil or mining works are typically excavated using an arched section, to obtain all the benefits of stress redistribution that compresses the geomaterial, taking advantage of its compressive strength and avoiding calling on its low tensile strength. The existence of planes of weakness may create instability issues related to the detachment or sliding of the layered rock structure when cut by an arched section.

The introduction of rockmass anisotropy due to discontinuities and its consequences on underground excavations is part of the first step/learning objective. It will determine the subsequent comprehension of the advantages offered by numerical simulations and the significance of validation. It may include any or all of the following topics of analytical solutions for the effect of the presence of one or more discontinuities with respect to the stress field, the discontinuity orientation and the excavation geometry.

2.3.1 Analytical examination of the effects of the presence of a single discontinuity with respect to the stress field and the excavation geometry

In this section, a simple mechanical model is considered: circular excavation cross section in hydrostatic stress field and the presence a single discontinuity in the rockmass, as depicted in Figure 2b. The Kirsch equations (Kirsch, 1898, Jaeger & Cook, 1979) are applied to define the shear and normal stresses on the single discontinuity wall surfaces at various inclinations.

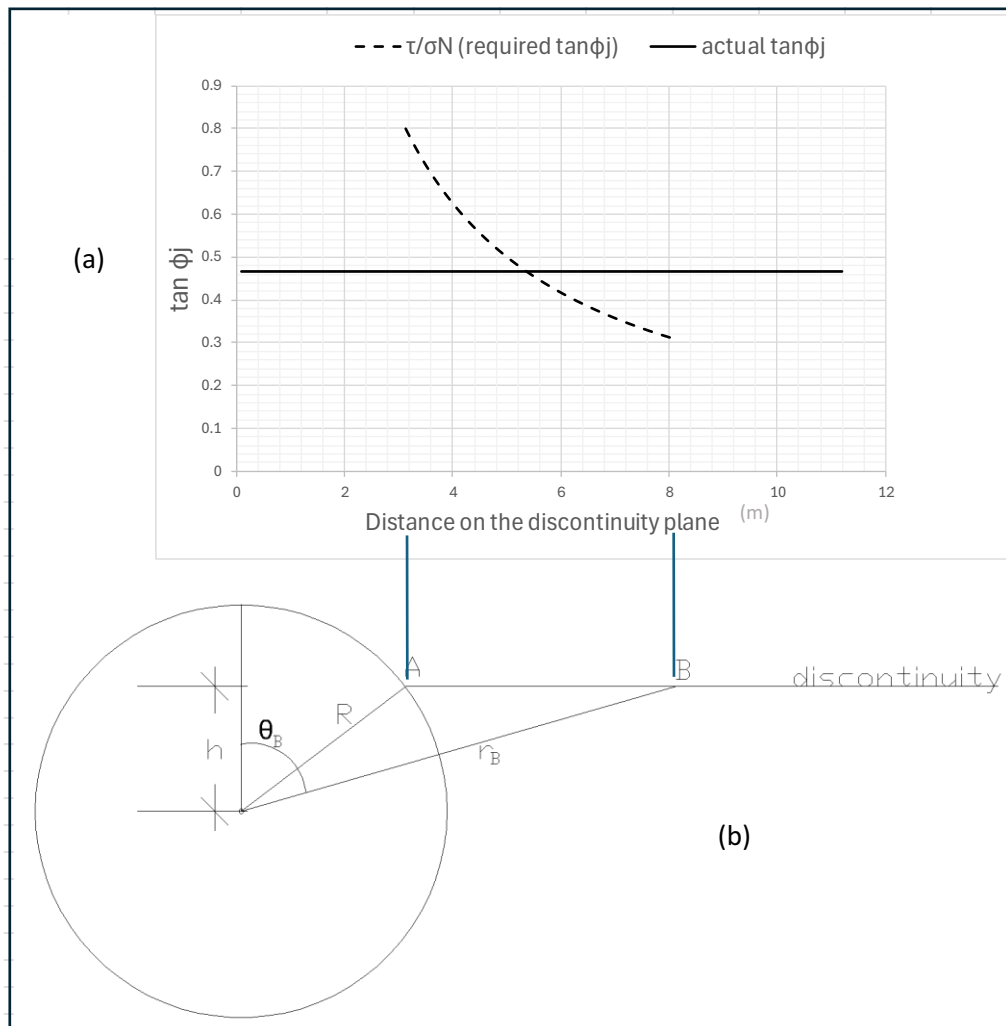


Figure 2. (a) Graph of friction requirements along horizontal discontinuity plane of $\phi_j=20^\circ$, met at a height of $h=3$ m by a tunnel of $R=4$ m radius, (b) Conceptual model and geometric details

The analysis of the stresses on a non-cohesive ($c_j=0$) discontinuity section AB leads to the definition of limit sliding state of Equation 1a, where τ and σ_N are the shear and normal stress on the joint surface and ϕ_j the joint friction angle (Equation 1b).

$$\frac{\tau}{\sigma_N} < \tan \phi_j ; \frac{\tau}{\sigma_N} = \frac{\left(1 - \frac{p_i}{p_0}\right) \frac{R^2}{r_B^2} \sin 2\theta_B}{1 - \left(1 - \frac{p_i}{p_0}\right) \frac{R^2}{r_B^2} \cos 2\theta_B} \quad (1a;b)$$

where p_0 is the in-situ stress, p_i the stress on the excavation boundary, R the circular excavation radius and r, θ polar coordinates. A comprehensive theoretical analysis may be found in Brady & Brown (1983) and Sofianos (2018).

Assessment of the students' work is based on the preparation of a graph of the friction angle requirement along the length AB of the discontinuity and can be performed in python, MATLAB, excel or any other coding package. A sample of what is expected from students is illustrated in Figure 2a. The educational goal is the evaluation of geometrical and mechanical parameter influence on the excavation failure due to the discontinuity presence. Further, the analytical solution graph will be used in the learning objective III of numerical validation in order to compare results.

2.3.2 Analytical examination of the case of circular opening in anisotropic stress field with a single inclined discontinuity

The same elastic stress distribution equations (Kirsch, 1989) are used for a geometric setup where the discontinuity passes through the tunnel centre. Various angles of inclination can be used, such as 0° , 30° , 45° and 90° . In all cases, the sufficiency of the resistance offered by the joint friction is calculated similarly and observed along a specific length of the discontinuity.

2.3.3 Analytical examination of ubiquitous joints

On the excavation wall, the only non-zero stress component is the tangential stress $\sigma_{\theta\theta}$. It is therefore easy to run all points on the excavation circumference by the test of friction angle sufficiency with respect to the angle δ formed by $\sigma_{\theta\theta}$ and the discontinuity unit vector. For the axisymmetric problem of circular cross-section in a hydrostatic stress field, four areas are defined on the circumference, of which two are stable and two unstable. The existing methodologies for the definition of these areas - so as to subsequently calculate the required support pressure to stabilize them - are three: graphical, analytical and numerical.

2.3.3.1 Graphical solution

Goodman (1980) illustrated the effect of joint slip by using a geometrical method to examine the extent of slip along the periphery of an underground opening. For a given cross section of the opening and friction angle ϕ_j of the joint planes, zones of joint slip with potential sliding and flexure on the periphery of an excavation of any shape can easily be identified by drawing two lines inclined at ϕ_j to the normal to the layers and tangent to the excavation periphery. Figure 2a depicts this method for a circle-shaped tunnel driven in a rock mass with one joint set dipping at an angle of 75° from the horizontal with joint friction angle equal to 30° . The method offers a fast and precise estimation of the zones that may slip at the tunnel periphery in the case of excavating in an anisotropic rock.

2.3.3.2 Analytical solution

In order to perform an analytical calculation of the extent of joint slip zones around circular tunnels, elastic rockmass is initially considered and the distribution of elastic stresses around the cavity is calculated as in previous § 2.3.1. Then, the elastic shear stress is compared to joint shear strength, considering a Coulomb slip criterion for the joint. The joint is considered to slip, when the elastic shear stress τ exceeds the joint shear strength τ_j . Therefore, slip zones identified analytically correspond to excess shear stress contours of $\tau/\tau_j \geq 1$. Daemen (1989) developed the closed form solution of Equation 2 to calculate the extent of the joint slip zones through the elastic rockmass around circular tunnels.

$$\left(\frac{r}{R}\right)^2 = \frac{(p-p_i)[S_e \cos 2(a-\theta) \tan \phi_j \pm \sin 2(a-\theta)]}{-S_e(c+p \tan \phi_j)}; \quad \frac{R_{max}}{R} = \sqrt{\frac{1-p_i/p}{\frac{c \cos \phi}{p} + \sin \phi}} \quad (2a;b)$$

where r, θ : polar coordinates, R : tunnel radius, R_{max} : maximum slip zone depth, p : in situ stress, p_i : support pressure, S_e : factor of discontinuities shear overstressing (τ/τ_j), $S_e=1$ is the limit state, α : dip angle of discontinuities. Figure 2b depicts the method results for a circular shaped section in a hydrostatic stress field and discontinuities inclined at $\alpha=30^\circ$ and joint friction angle $\phi_j=20^\circ$. According to Equation 2b, the maximum slip zone depth is independent of the dip.

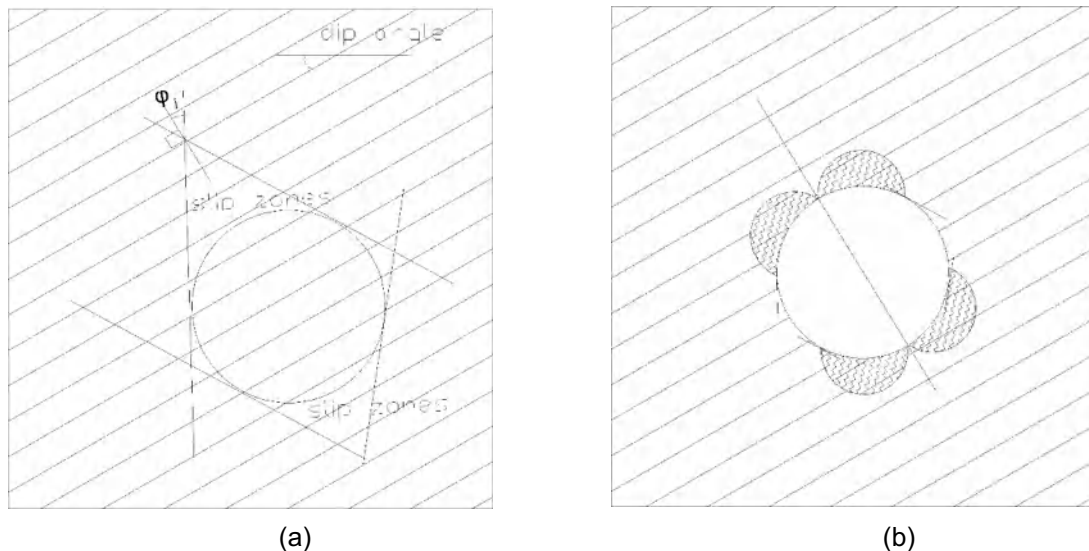


Figure 2. Slip zones around circular excavation in isotropic stress field and rockmass with single joint set dipping at an angle of 30° . (a) Graphical solution (§ 2.3.3.1.) – slip occurs at any periphery point within the slip zones (b) Analytical solution (§ 2.3.3.2.) - at any point within the shaded areas the shear stress exceeds the shear strength

The slip zones calculated by the solution of Daemen (1989) according to Equation (2) for different joint cohesion and joint friction angle is the second assignment on which the first learning step, i.e. theory and analytical solution, is assessed. At the end of this assignment the students will be able to obtain the analytical solution for all parameter ranges and experiment with various rock formations. For example, for an unsupported circular opening in a formation with zero cohesion of the joints, they can study the effect of the joint friction angle on the extent of the slip zone. Another alternative for more mature students, is to apply a flipped classroom scheme: the research paper by Daemen (1989) is provided along with a brief walkthrough during the lecture and they are called to present it to the classroom themselves based on their own work.

This concludes the first section of Theory and analytical solution. In order to introduce the next step, a question is posed to the learners: Does the analytical solution take into account the redistribution of stresses around the opening due to the joint slip? The ensuing discussion leads naturally to the conclusion that to further investigate any effect of such stress redistribution on tunnel behaviour, numerical analysis is needed.

3 Numerical solution

Having seen the usefulness but also the limitations of the graphical and analytical method, the students will now be called to use the numerical method to perform a more advanced analysis, closer to the reality of jointed rockmass. They would first be given a simple setup, e.g. according to the previous paragraphs 2.3.1 or 2.3.2, that will yield results almost identical to the analytical solution they will have performed with their python/matlab/excel code.

3.1 Ubiquitous joint model

Time Frame 3 Training and PCLab activities (Figure 1) are at this stage beginning. The students have had the opportunity to acquire sufficient knowledge and insight to develop their approach to the problem by using numerical analysis. Numerical codes that do not employ the discrete element method may simulate the anisotropy brought about by a discontinuity set through the constitutive model of ubiquitous joints. This is a post-analysis feature based on the results of the finite element analysis performed by the students. It is therefore not expected to provide different results when the numerical analysis is elastic as compared to the analytical solution. The elastic stresses are calculated numerically and then the slip criterion is applied according to the stress distribution around the cavity. This constitutive model is related to continuum analysis and should be the first numerical approach for the student. Continuum

analyses can be quite efficient computationally and can be used routinely to represent laminated materials through the implementation of the ubiquitous joint model (Sainsbury & Sainsbury, 2017).

Laboratory numerical work in a PCLab and continuum numerical analysis followed by presentation of the results and subsequent discussion of the above remarks is the proposed scheme for the first numerical implementation during Time Frame 3. There are open-access, and subscription finite element software packages that can be used in classroom, by remote connection to a server or other cloud solutions. At the end of this section, the first comparison between the analytical and the numerical solution is carried out. The expected result is known, and this serves as guidance for the self-study of the students.

3.2 Discrete element modelling

This section is the more advanced numerical modelling where the presence of discontinuities is explicitly included in the numerical model. This will require the input of details difficult to obtain in a deterministic fashion, such as joint stiffness and joint spacing. The effect of joint stiffness on the numerical model solution is a good choice to focus on, during the comparison to the analytical solution. The significance of model validation against the analytical solution will become evident; joint stiffness and deformability is a fundamental topic of rock mechanics (Bandis et al., 1983) and numerical simulation is ideal in obtaining a clear visualization from parametric analyses of how results can differ according to these parameters. It is proposed to vary joint stiffness parameters over 3 orders of magnitude and four cases of discontinuity spacing. Table 2 contains an example set of combination values for joint shear and normal stiffness and joint spacing and respective results expressed in terms of joint slip arc length L on the excavation periphery and joint slip depth $R_{\max}$ from the center of the excavation.

Table 2. Numerical method results for joint slip arc length L and joint slip depth $R_{\max}$ with respect to analytical solution for three cases of joint stiffness and four cases of joint spacing (Yiouta-Mitra et al., 2015)

Joint stiffness normal ; shear (MPa/m)	Joint spacing				Analytical solution
	5 m	2.5 m	1 m	0.5 m	
(i) $10^6; 10^5$	- $R_{\max}=11.2$ m	$L=5.2$ m $R_{\max}=10.56$ m	$L=5.8$ m $R_{\max}=10.56$ m	$L=5.8$ m $R_{\max}=10.78$ m	
(ii) $10^5; 10^4$	- $R_{\max}=9.96$ m	$L=5.2$ m $R_{\max}=9.96$ m	$L=4.62$ m $R_{\max}=9.4$ m	$L=5.2$ m $R_{\max}=8.86$ m	$L=5.9$ m $R_{\max}=8.43$ m
(iii) $10^4; 10^3$	- $R_{\max}=7.07$ m	- $R_{\max}=7.07$ m	$L=3.5$ m $R_{\max}=7$ m	$L=4$ m $R_{\max}=6.73$ m	

The areas where the joint shear strength is exceeded define the maximum slip zone depth $R_{\max}$ and an arc of length L on the periphery of the excavation, as shown in Figure 4. These quantities shall be measured from the numerical model and compared against the analytical solution by the students.

According to their parametric results, the best overall accordance to the analytical solution shall be calculated for normal and shear stiffness respectively and for spacing of discontinuities. For the example of Table 2, the lowest divergence from the analytical solution (see last column) for the quantities of L and $R_{\max}$ is observed for normal ; shear stiffness at $10^5; 10^4$ MPa/m, respectively, and for spacing of discontinuities at 50 cm. In terms of % divergence, the best cases are 11% and 5% while the worst 32% and 20%, respectively. The absolute values correspond to a case of a circular opening of $R=5$ m, hydrostatic field and in situ stress $p_0=2.6$ MPa, equivalent to an overburden of 100m of hard rock. The values of normal and shear stiffness were estimated from rock mass modulus, intact rock modulus and joint spacing, according to Barton (1972) and the following Equation 3, assuming that the deformability E_m of a rock mass is due to the deformability of the intact rock E_i and the deformability of the joints in the rock mass:

$$\frac{1}{E_m} = \frac{1}{E_i} + \frac{1}{k_n S} \rightarrow k_n = \frac{E_i E_m}{S(E_i - E_m)} \quad (3)$$

where k_n = joint normal stiffness and S = mean joint spacing.

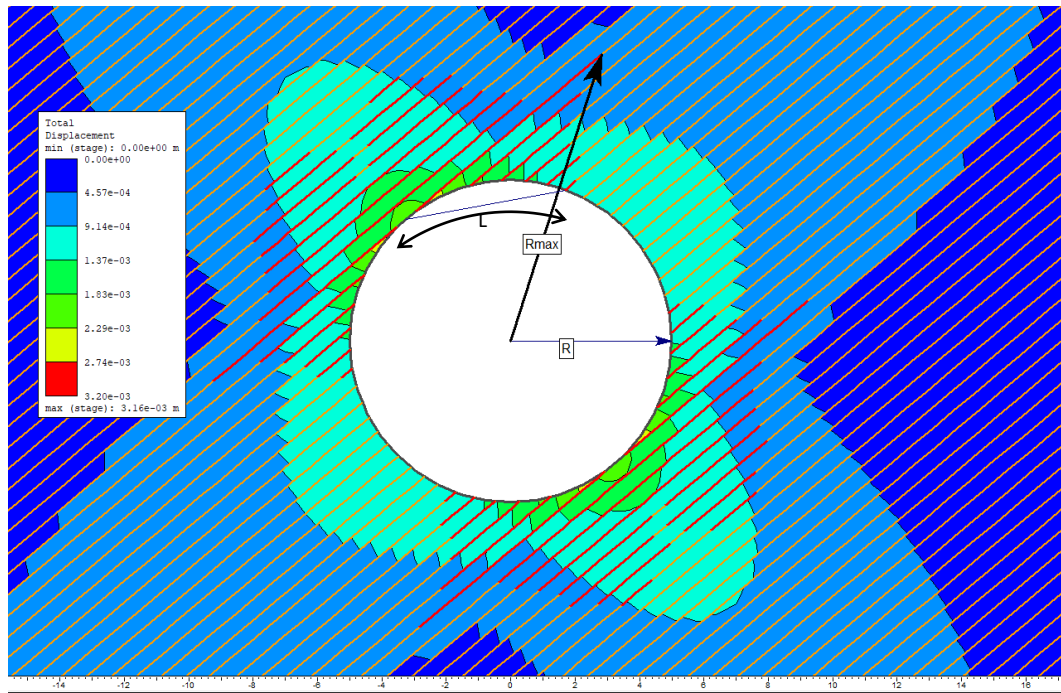


Figure 4. Measurement of R_{max} and slip arc length L for circular opening in jointed rockmass inclined at 40° and joint spacing at 50 cm. Results from numerical solution

Clearly, the spacing of discontinuities and their normal and shear stiffness play an important role for the shear strength exhibited. A denser joint network approximates better the analytical solution when joints are given their stiffness according to Equation 3. Figure 5 depicts the effect of discontinuity stiffness for two cases of Table 1 and is generated by students and their numerical results.

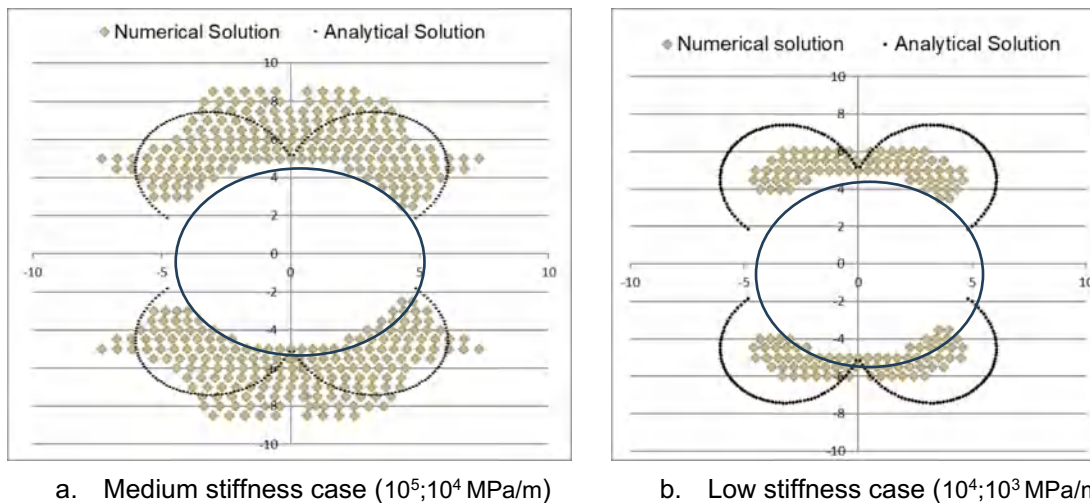


Figure 5. Comparison of zone slip areas according to analytical solution and FE with joint elements solution for (a) medium and (b) low joint stiffness rockmass, at 0° inclination around circular opening

This procedure increases the learning achievement and problem-solving skills for the students who generated the results required for the model validation. Using the students' own opinion and their results in a classroom discussion, the following conclusion is naturally reached: the numerical solution includes effects of parameters not considered in the analytical solution and a joint properties baseline should be drawn for the examination of subsequent parameters, such as the influence of the redistribution of stresses around the opening due to the joint slip or the effect of the plasticity of the rockmass or the effect of the cross sectional shape.

4 Problem-based case study

This last level in the comprehension and calculation of the anisotropic effects of rock discontinuities requires real monitoring data from a suitable actual underground project. As already mentioned, in PBL it is not the teacher who passes on new knowledge to the students, but they themselves realize what knowledge is still lacking to solve the problem. Therefore, this last stage is based on distributing to the students parts of a publication containing details of an actual project that fits the specific rock mechanics topic and ask them to identify the stability issues and to perform the required support calculation on their own, by applying all previous steps. A project suitable for PBL in the case of jointed rock behaviour and underground excavations is the Kalydona tunnel, part of the Greek Highway Ionia Odos, which connects Antirion to Ioannina (Yiouta-Mitra et al., 2011). It was excavated in undisturbed flysch formation and low stress environment due to low overburden. Additionally, a high strength over stress ratio excludes the possibility of stress failure of the rockmass. The drill and blast method was used. The only factor of instabilities is the discontinuities, especially the rock layers created during the sedimentation phase and the potential of slip on their surfaces. This allowed light support measures, big round lengths and for one half of the tunnel, full face excavation. In the tunnel periphery, at the shoulders, minor over-excavations have been observed and been dealt with through an amelioration of the blast design according to smooth blasting technics. The tunnel excavation was successfully completed. Geotechnical categories provided by the tunnel designer are included in Table 3, with information on Rock Quality Designation (RQD), lithology, Rock Mass Rating (RMR) and uniaxial compressive strength (σ_c).

Table 10. Rock mass categories and characteristic uniaxial compressive strength

Rock Mass	A	B	C	D
RQD	70-100	70-100	40-60	40-60
Lithology	Sa	Si	Sa	Si
RMR ₈₉	65-78	52-67	50-63	42-53
σ_c (MPa)	50-55	15-20	50-55	15-20

The students are assigned the analysis of excavation by considering the anisotropic nature of the flysch rockmass. It may be performed by using the three different methods: geometrical, analytical and numerical. All methods provide a fair estimate of the area of joint slip and the required temporary support pressure for stability. In the case of the numerical method, the application of the ubiquitous joint model yields good results. Figure 6 contains the comparison of finite differences numerical code displacement results to a selected monitored tunnel cross-section, which can be used as the alternative for the validation. According to this figure, very good agreement in joint slip behaviour as well as in monitored and calculated displacements is achievable, so this project constitutes good educational material. All project details can and should be retrieved by the students' personal perusal and research.

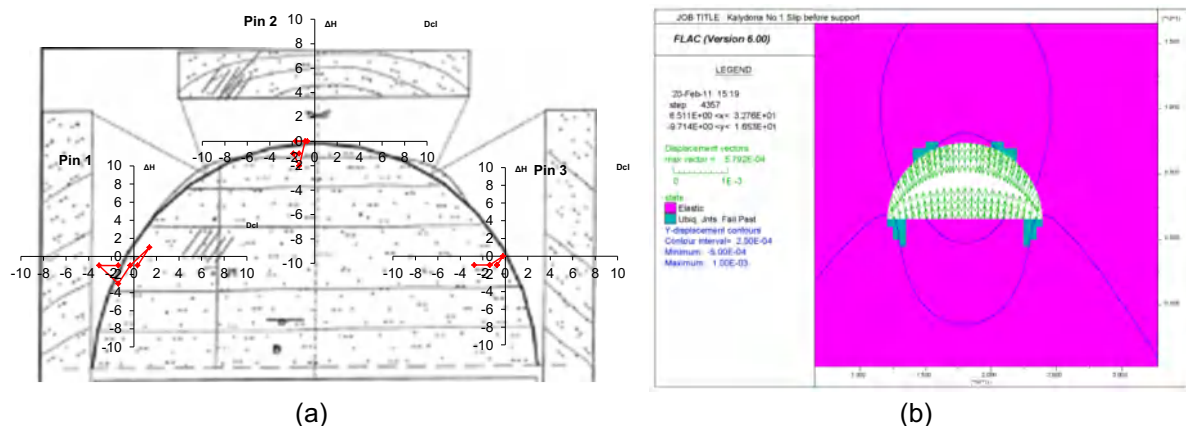


Figure 6. (a) Face mapping and geodetic monitoring at selected cross-section, (b) Areas of slipped joints with use of ubiquitous joint model for Kalydona selected cross-section (after Yiouta-Mitra et al., 2011)

5 Summary

In this paper, a roadmap to modernized rock mechanics education is developed through four basic steps. The specific topic of rock anisotropy and its effects on underground structures stability is considered and guidelines are provided for a more engaging pedagogy. The topic is currently included in undergraduate and post-graduate specialized courses on support of underground works and rock mechanics. The methodology and significance of numerical model validation is depicted in a meaningful way and a deeper understanding of the tools available to engineers is achieved.

Declarations

Sample code and numerical models can be provided to interested educators on personal demand from the author. The complete simulation that yielded the results of Figure 4 can be downloaded at this [link](#).

References

- Akinoğlu, O., Özkardeş Tandoğa, R. (2007). The effects of problem-based active learning in science education on students' academic achievement, attitude and concept learning. *Eurasia Journal of Mathematics, Science & Technology Education*, 3(1), pp. 71-81.
- Ali, S.S. (2019). Problem Based Learning: A student-centered approach. *English Language Teaching*, 12, pp. 73-73.
- Bandis, S.C., Lumsden, A.C., Barton, N.R. (1983). Fundamentals of rock joint deformation, *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 20(6), pp. 249-268.
- Barton, N.R. (1972). A model study of rock-joint deformation, *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 9(5), pp. 579- 602.
- Barrows, H. (1998). The essentials of problem-based learning. *Journal of Dental Education*, 62(9), 630-633.
- Brady, B.H.G., Brown, E.T. (2004). *Rock Mechanics for underground mining*, 3rd edition, Kluwer academic publishers, Dordrecht, Netherlands.
- Daemen, J.J.K. (1983). Slip zones for discontinuities parallel to circular tunnels or shafts. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 20(3), pp.135-148.
- Goodman, R.E. (1989). *Introduction to Rock Mechanics*. Wiley, New York, USA.
- Jaeger, J.C., Cook, N.G.W. (1979). *Fundamentals of Rock Mechanics*, 3rd edition. Chapman & Hall, London, UK.
- Kirsch, G. (1989). Die theorie der elastizität und die bedürfnisse der festigkeitslehre. *Zentralblatt Verlin Deutscher Ingenieure*, 42, pp. 797-807.
- Nilson, L.B. (2010). *Teaching at its best: A research-based resource for college instructors*, 2nd edition. John Wiley & Sons, San Fransisco, USA.
- Sainsbury, B.L., Sainsbury, D.P. (2017). Practical Use of the Ubiquitous-Joint Constitutive Model for the Simulation of Anisotropic Rock Masses, *Rock Mechanics and Rock Engineering*, 50, pp.1507–1528.
- Sofianos, A. (2015). *Underground Support Measures*, Kallipos Open Academic Editions, Athens, Greece.
- Yiouta-Mitra, P., Prountzos, N, Sofianos, A.I. (2015). A parametric study for the strength of jointed rock mass. In: *Proceedings of the ISRM Regional Symposium EUROCK 2015 & 64th Geomechanics Colloquium - Future Development of Rock Mechanics*, Schubert, W. & Kluckner, A. (eds), pp. 919-924. Austrian Society for Geomechanics: Salzburg, Austria.
- Yiouta-Mitra, P., Steiakakis, C, Merziotis, D, Nomikos, P.P., Sofianos, A.I. (2011). Ionia Odos: Tunnelling through undisturbed anisotropic flysch formation. 1st Scientific Congress on Tunnels and Underground Structures in South-East Europe "USING UNDERGROUND SPACE", Davorin Kolić (Eds), Promovere, Dubrovnik, Croatia.

Author's bio

Paraskevi Yiouta-Mitra, National Technical University of Athens (Greece)

Dr. Paraskevi Yiouta-Mitra is permanent teaching staff at the National Technical University of Athens. She specializes in the field of Rock Mechanics and Computational Engineering. She holds her Mining and Computational Engineering degrees from the same University. Her disciplinary research interests involve, among others, the use of advanced simulation techniques, the behaviour of fractured rockmass and the design and construction of mining and civil underground works. She has more than 25 years of experience in university teaching and an unwavering interest in STEM education. She has been member of the Tunnelling Laboratory of the School of Mining and Metallurgical Engineering since its foundation in 2003. She is former vice-president of the Greek Tunnelling Society and is currently leading the organization of the International Day of Women in Mining in Europe. She is a volunteer for the hour of code in Greek public schools and has coached award-winning student STEM teams for the WRO-Hellas robotics competition.

Author Index

- Abdallah, A. 329, 371
 Abed, A. 429
 Airey, D. 223
 Ajmera, B. 89
 Alonso, E.E. 459
 Amabile, A. 23
 Ancia, P. 113
 Araújo Santos, L. 339
 Arnold, A. 235

 Barreto, D. 235
 Beckett, C.T.S. 483
 Bicalho, K.V. 439
 Bohnhoff, G. 293
 Borges, J.L. 495
 Brezzi, L. 415
 Budach, C. 257
 Burecic Safran, M. 125

 Calvello, M. 387
 Capobianco, V. 101
 Ceccato, F. 43, 415
 Chalmers, T. 181
 Chung, P. 89
 Cuccurullo, A. 361
 Cuira, F. 211
 Cuisinier, O. 329, 371
 Cupillard, P. 371

 da Silva Burke, T.S. 199, 471
 Dalla Santa, G. 415
 Deck, O. 351
 Descamps, F. 113
 Dimitriadi, V. 235
 Diraison, M. 371

 Emery, A. 89

 Faÿ, O. 113
 Fellin, W. 303, 401

 Gabrieli, F. 415
 Géraud, Y. 371
 Gilbert, G. 101
 Golfier, F. 371
 Gonze, N. 113

 Hubler, J. 393

 Hunt, D.V.L. 149

 Jefferson, I. 149
 Jenck, O. 245
 Josifovski, J. 161
 Jovanovski, M. 161

 Karstunen, M. 429
 Kirsch, A. 257, 401
 Kluge, K. 257
 Kovacevic Zelic, B. 125
 Kwon, T.H. 101

 Leak, J. 235
 Ledesma, A. 447

 Macedo, J. 519
 MacRobert, C.J. 137, 471
 Mangraviti, V. 415
 Maraš, M. 161
 Masrouri, F. 329
 Matos Fernandes, M. 495
 Moghaddasi, H. 507
 Monzer, A. 149
 Moradi, M. 507
 Muguda, S. 361

 Nikiema, T. 113
 Nishii, R. 101

 Ogwezi, B. 507
 Okyay, U.S. 269
 Oltean, C. 371

 Pantazidou, M. 3, 315, 495
 Papić, J. Br. 161
 Park, J.Y. 101
 Pereira, J.M. 211
 Peševski, I. 161
 Piciullo, L. 101
 Pinho-Lopes, M. 519, 533
 Pinyol, N.M. 447, 459
 Poplin, A. 89
 Powrie, W. 533
 Prat, P.C. 447
 Proença, S. 339

 Ramon, A. 447

 Ribeiro, V. 339
 Ricotier, D. 245
 Romero, E. 447
 Royal, A. 149
 Rutherford, C. 89

 Sabrowsky, J. 89
 Salifu, E. 361
 Sample-Lord, K. 293
 Sausse, J. 371
 Seo, H. 169
 Shields, C.H. 181
 Sonnenberg, R. 401
 Steenkamp, J.D. 281
 Strandberg, N. 293

 Tang, A.M. 211
 Tantivangphaisal, P. 547
 Tarantino, A. 23, 507
 Theron, E. 281, 559
 Toms, C.T. 181
 Tshibangu, J.P. 113
 Tsiampousi, A. 547

 Utter, N. 53
 Uzielli, M. 101

 Vandamme, M. 211
 Vandycke, S. 113
 Vogt, H. 235
 Vosloo, P. 281
 Vulpe, C. 483

 Walleser, J. 293
 Watanabe, N. 101
 Waters, S.G. 281, 559

 Xenaki, V. 315

 Yap, T.Y. 181
 Yi, M. 169
 Yiouta-Mitra, P. 571

 Zhu, J. 223
 Znidarcic, D. 125
 Zornberg, J.G. 63



ISBN: 978-618-84925-1-6

ISSN: 2732-7256