6th ATHENIAN GEOTECHNICAL LECTURE

INTERACTION BETWEEN STRUCTURAL AND GEOTECHNICAL ENGINEERS

Based on paper published in The Structural Engineer 18 April 2006

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Structure-Ground Interaction

- Interaction always takes place between a structure and its foundation ….. **<u>whether or not the designers allow for it</u>**

- In some situations it can be minimised e.g. very stiff piles

- This approach can be costly and is often not feasible e.g.deep basements

- If structure-ground interaction is to be taken into account in design, Structural and Geotechnical Engineers have **<u>themselves</u>** to interact.

Communication between Structural and Geotechnical Engineers

- The Author has both witnessed and experienced difficulties in communications between Structural and Geotechnical Engineers
- These difficulties are clearly a matter of considerable importance
- This has caused me to explore some of the reasons for these difficulties
- I have come to the conclusion that, at the heart of the problem, there are differences in the approach to **<u>modelling</u>** the real-world situation
- **I will try not to side with either of the disciplines - the objective is to improve understanding of the way the "average" practitioner tackles design**

Contents

Structural and Geotechnical Modelling

Applications of ductility in Foundation Design

Two case histories in which understanding the mechanisms of behaviour provides the key:

The failure of some silos during discharge – due to soil-structure interaction?

An historical example of soil-structure interaction

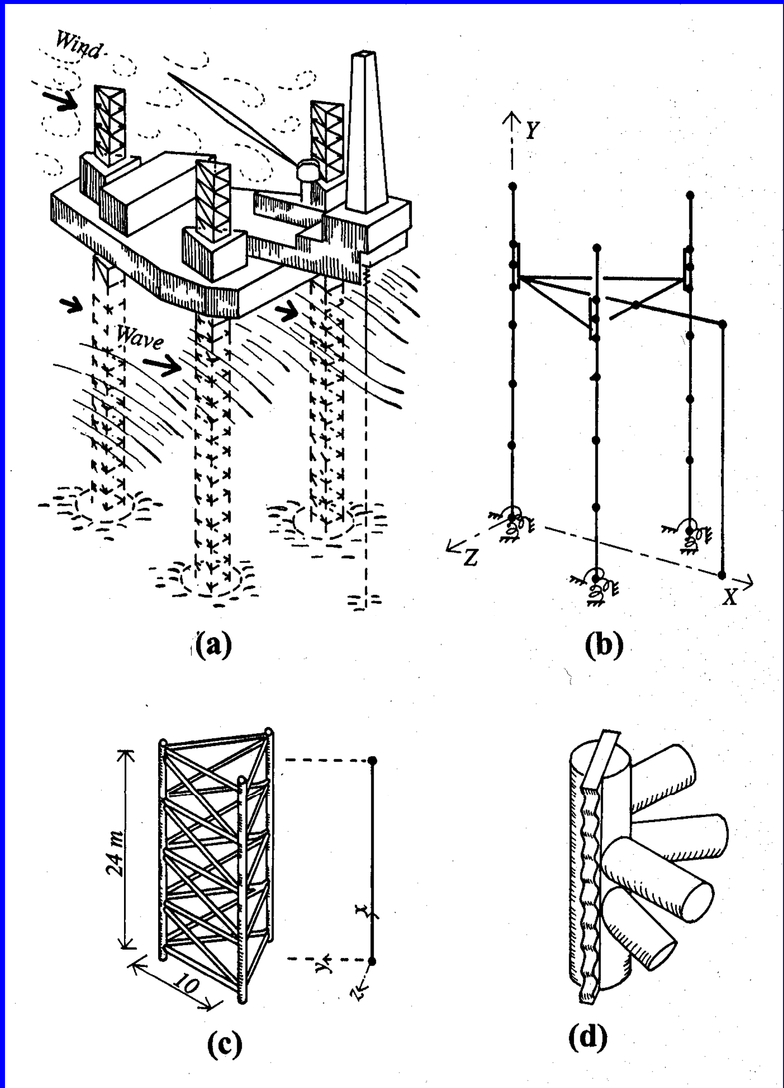
Modelling

- "The process of **idealising** the full-scale project, including the geometry, material properties and loading …….
- in order to make it amenable to **analysis** and hence assessment for *fitness for purpose*"
- **Thus the process of modelling is very much more than simply carrying out an analysis**.

Structural Modelling

- *“Structural Analysis by Example”* by E.C. Hambly.
- Fifty examples of increasing complexity covering the range of problems and types of analysis encountered by most Structural Engineers in day to day practice.
- It is evident that the **geometry** is usually reasonably easy to idealise.
- Simple **material behaviour** is usually assumed - linearly elastic with a limiting stress specified. In exceptional cases a full elastic-plastic analysis will be carried out.
- The major **idealisations** seem to be in the loading, choice of load factors and material factors - but these are usually specified in Codes and Standards.
- See example of jackup offshore platform

Jackup Offshore Platform (after E.C.Hambly)



(a) Prototype structure

(b) Space frame model for global analysis

(c) Model of part of a leg

(d) Finite element model of joint

Structural Modelling

- **Almost all of the examples focus on the calculation of forces and stresses.**

- If deflections are calculated they are usually in the elastic range

- There is an increasing resort to the use of powerful computer programs …..

- Dare I say …. and to believe the output

Limitations to Structural Modelling

- Most studies on whole building structures show that the measured forces and stresses bear little semblance to the calculated ones (Walley, 2001)
- Ministry of Defence Building in Whitehall (Mainstone, 1960)
- Large-scale steel frame structures begun in the 1930's (Baker *et al.*, 1956).
- I have been involved in many cases of movements induced by subsidence where great concern is expressed. We have found that in many cases the thermal movements on buildings exceed the predicted subsidence movements (Burland *et al.*, 2001).

Ductility and Robustness

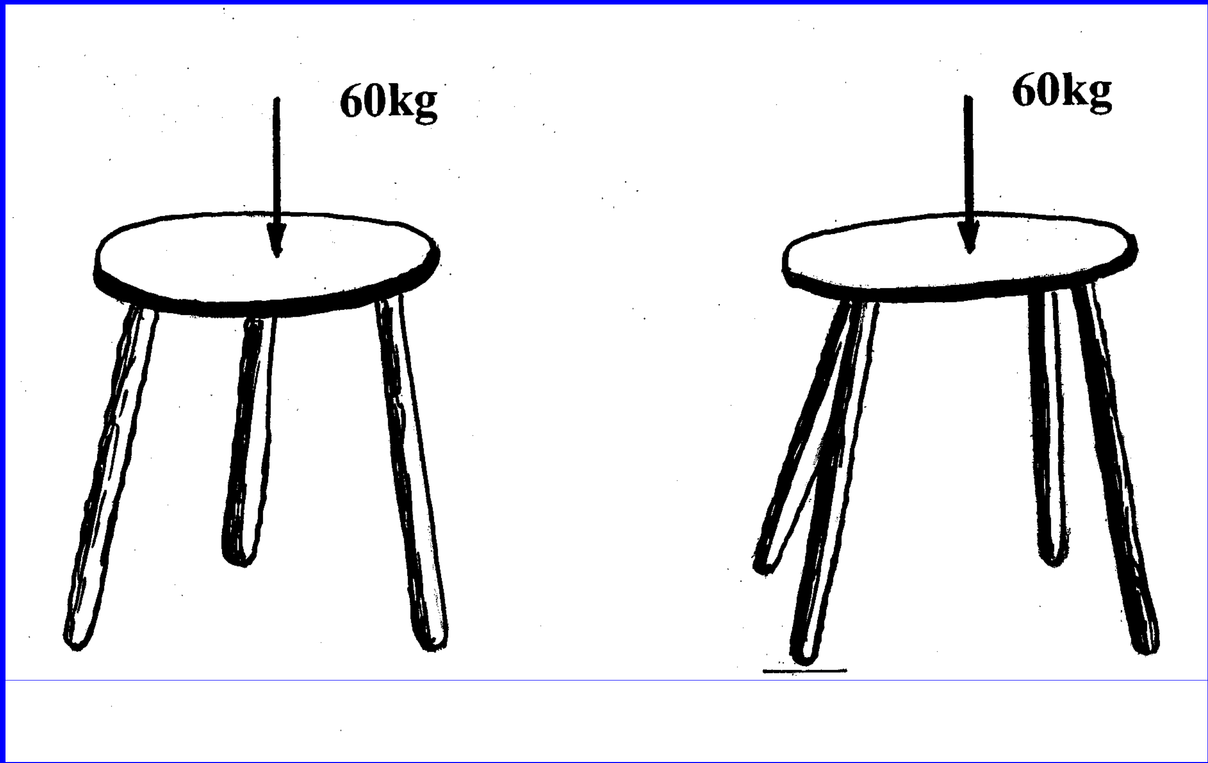
- Appreciation of these limitations have been known for a long time but are easily forgotten.
- Current routine approaches work because our codes usually ensure that our structures are ductile:
  - Steel members
  - under-reinforced beams
  - ***"weak-beam strong-column"*** philosophy

- Recently Beeby (1997, 1999) stressed the importance of designing for ductility and robustness in r.c. design.
- Modern earthquake engineering is focusing on this as well.

The Safe Design Theorem

- Hambly recognised that current design methods work for ductile structures because of the Safe Design Theorem:
- A structure can carry its design loads safely if:
  - The calculated system of forces is in **EQUILIBRIUM**
  - Each component has the **STRENGTH** to transmit its calculated force and the **DUCTILITY** to retain its strength while deforming
  - The structure has sufficient stiffness to keep deflections small and **AVOID BUCKLING** before design loads are reached (Note the importance of examining the details of connections and propping points)
- Thus, if the real structure deforms under load with a different flow of forces from that calculated, it will still be safe as long as the materials are **DUCTILE** and not **BRITTLE**, and if there is no risk of local instability.

Hambly’s Paradox - Royal Institution Childrens’ lecture



- What load is carried by each leg?
- What load should each leg be designed to carry?

This question is profoundly influenced by the brittleness of the material, the *fitness for purpose* and a knowledge of the boundary conditions

The boundary conditions are often unknown and unknowable

Ductility and Robustness

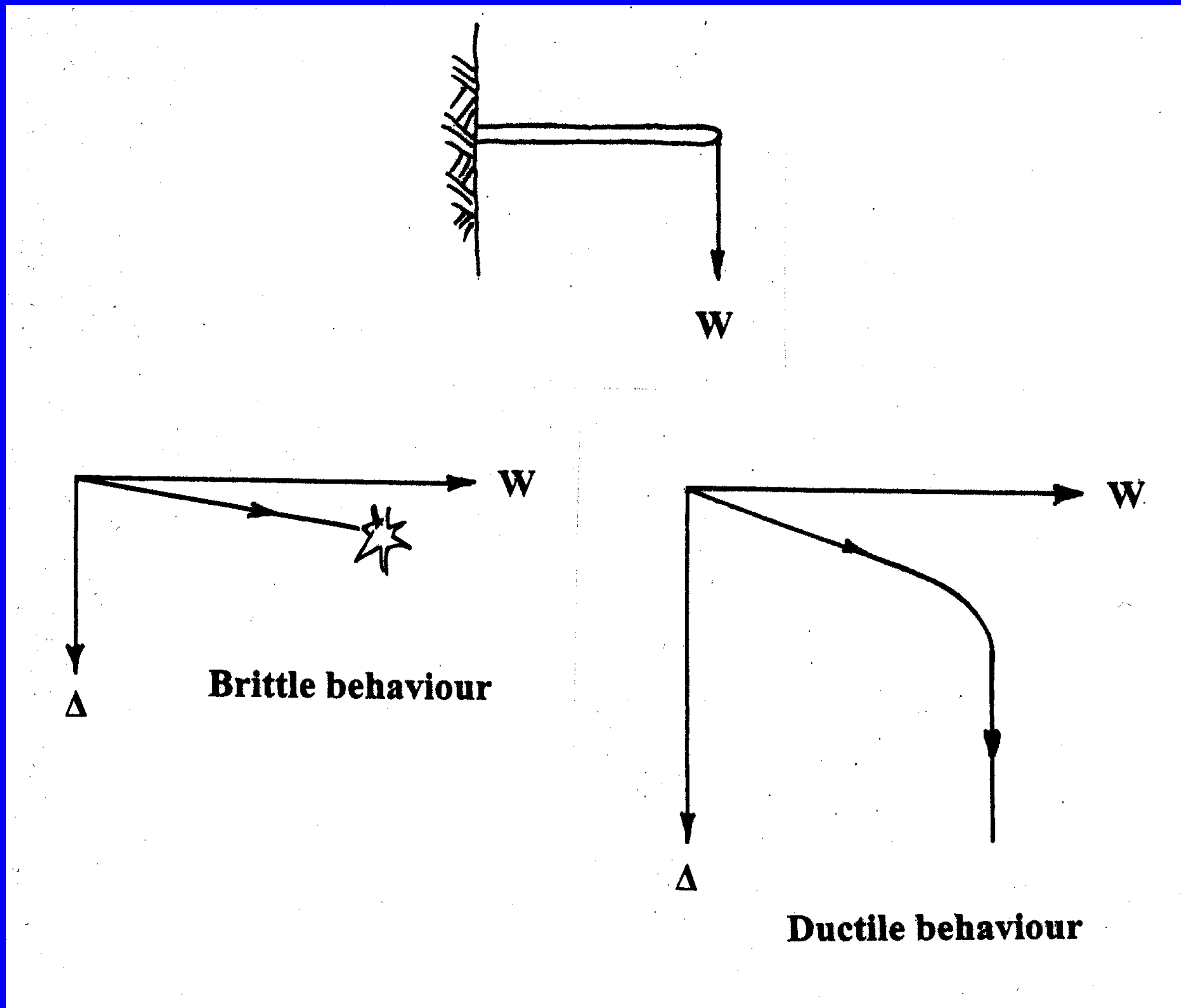
- Ductility:

  “The ability to undergo inelastic deformations without significant loss of strength”

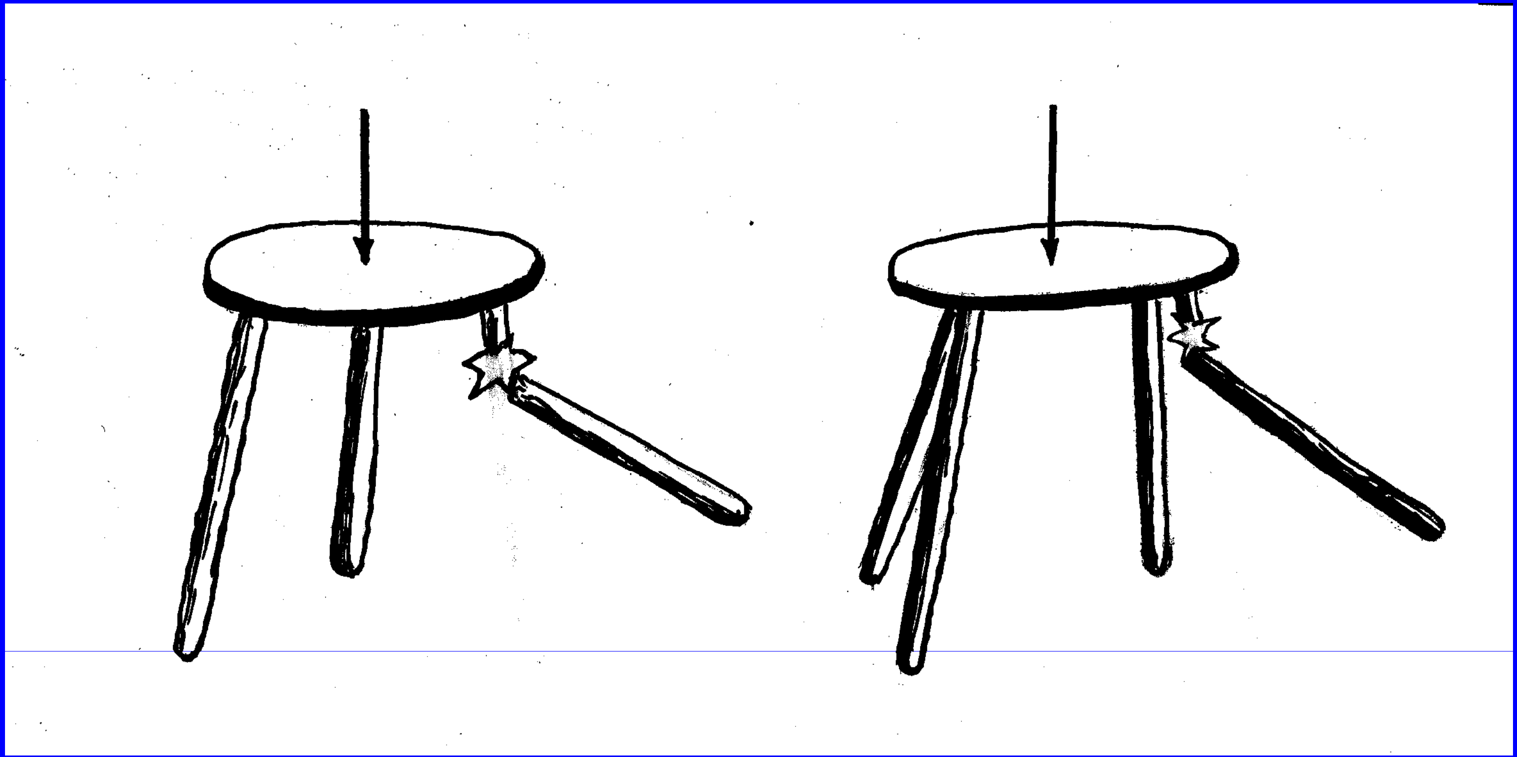
- Robustness:

  “The ability to absorb damage without collapse”

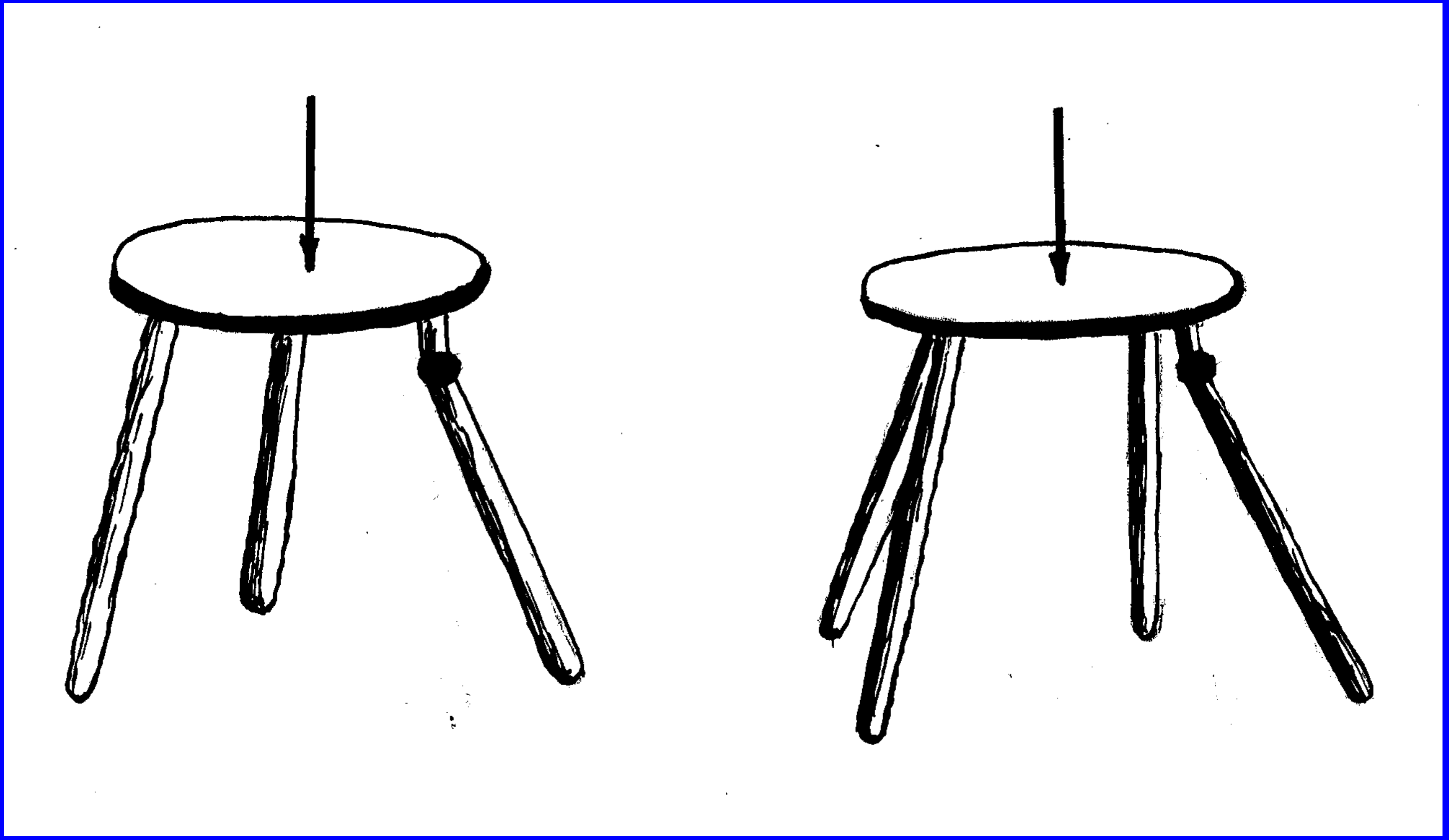
Brittleness and Ductility



Fragile Behaviour



Robust Behaviour



Heyman’s conclusion on Hambly’s Paradox:

• Hambly’s four-legged stool stands for the general problem of design of any redundant structure.

• To calculate the ‘actual’ state, all three of the basic structural statements must be made - equilibrium, material properties and deformation.

• Calculations do not in fact lead to a description of the actual state.

- – Boundary conditions are often unknown and unknowable
- – An imperfection in assembly, or a small settlement of a footing, will lead to a state completely different from that calculated

• This is not a fault of the calculations, whether elastic or not, it is a result of the behaviour of the real structure.

• There is no correct solution, but there is one that will lead to the greatest economy of materials - provided there is no inherent instability. Heyman (1996)

Recent publications on calculating the state of structures

- Burgoyne (2004): “Are structures being repaired unnecessarily”
- Mann (2005): Correspondence in Verulam
- Heyman (2005): “Theoretical analysis and real-world design”
- Mann (2006): “The interpretation of computer analysis”
- All these, and many more stress the difficulty of calculating the state of a structure and our reliance on the safe theorem in our designs and assessments

Geotechnical Modelling

Why is Geotechnical Modelling regarded by many engineers as a difficult subject?

- It is a difficult material:
  - Particulate with little or no bonding between particles
  - Stiffness and strength not fixed - depend on confining pressure
  - Dilates or contracts during shearing
  - Particles can change orientation during shearing
  - Arching action
- Water pressures acting within the pores are just as important as applied boundary stresses.
- We have to model the material as a continuum but we must never forget that it is particulate.

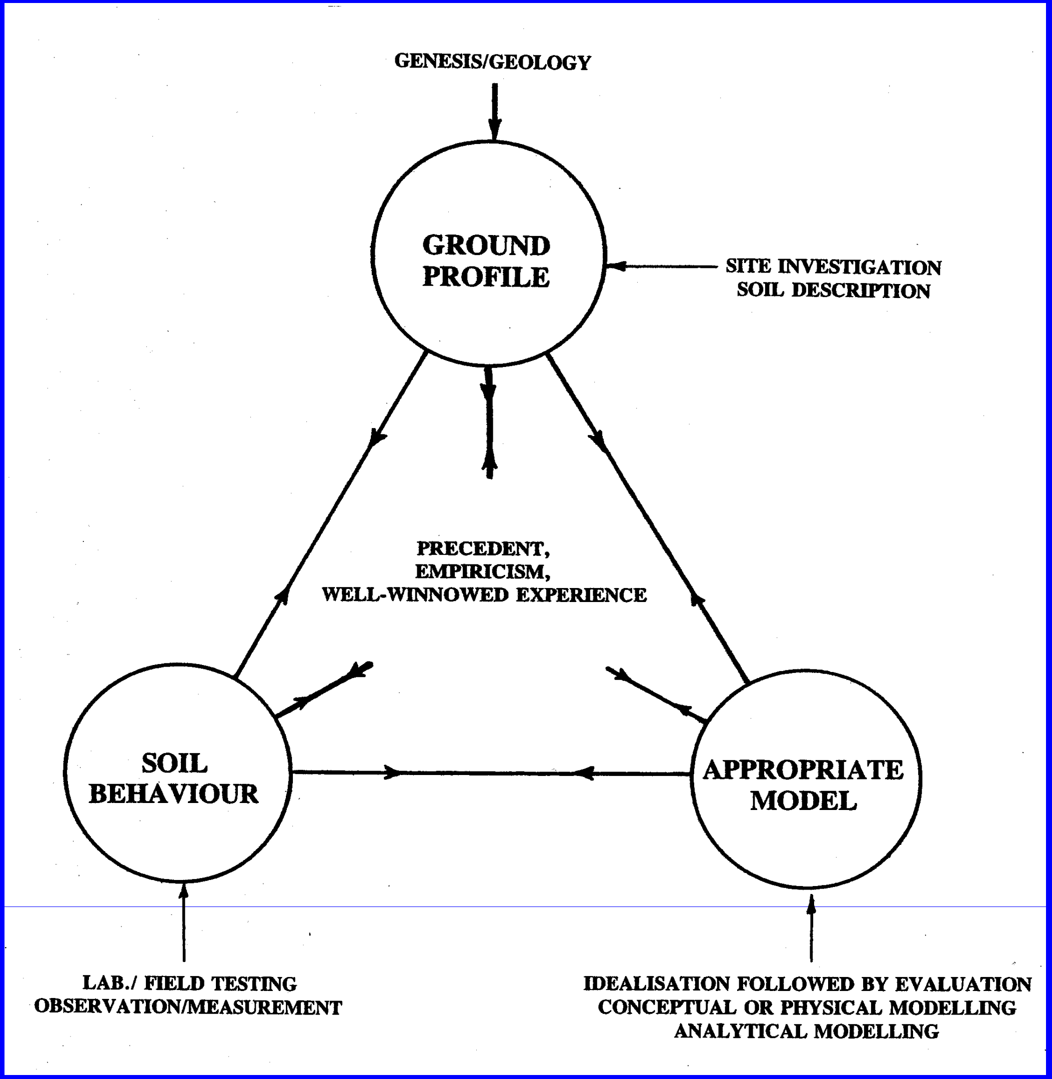
- **But modelling the material is not the only problem**

Geotechnical Modelling

There are at least four distinct but interlinked activities in geotechnical modelling:

- Finding out what is there and how it got there - **ground exploration and geology**.
- Determining the material properties of the ground by **laboratory or *insitu* measurement** or **back-analysis of full-scale behaviour**.
- Developing an **appropriate model for analysis**. (*It may range from purely conceptual to very sophisticated but it must capture the essential mechanisms of behaviour*)
- Using **precedent** and **well-winnowed experience** both in developing and interpreting the model (*separating the wheat from the chaff*)

The Geotechnical Triangle



The four activities are distinct but interlinked

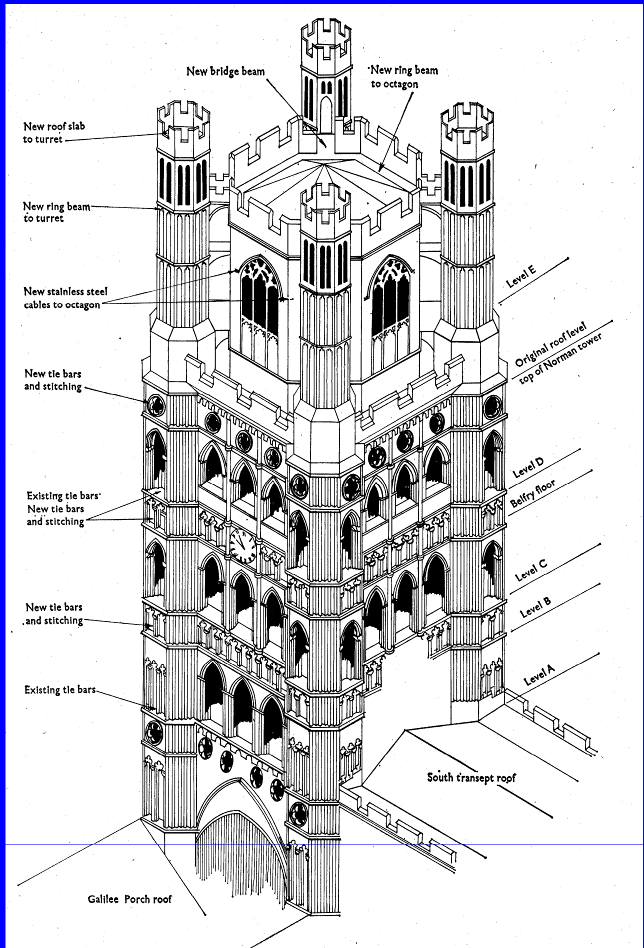
Comparison of Structural and Geotechnical Modelling

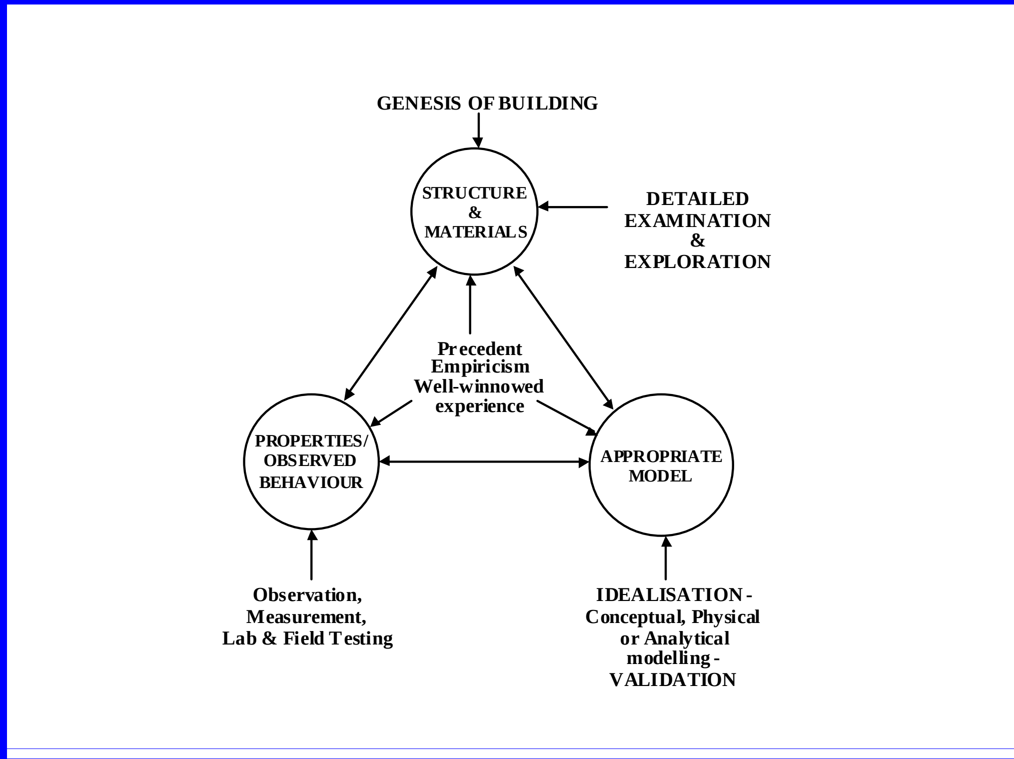
- For routine modelling the Structural Engineer specifies the material and the geometry. The uncertainties of ‘actual’ material properties and ‘lack of fit’ are often ‘hidden’ in the material and loading factors. There is a huge temptation to believe that a calculation represents the “actual state”.

- In geotechnical modelling both the geometry (ground profile) and the properties (ground behaviour) are laid down by nature and are seldom specified. It is more obvious that precise analysis is not possible. The key requirement is to understand the dominant mechanisms of behaviour and the likely bounds.

- In order to understand the processes that a geotechnical engineer goes through in modelling a problem, it is helpful to consider the investigations that a Structural Engineer has to undertake when modelling an existing historic structure - the two are remarkably similar.

West Tower of Ely Cathedral (After Heyman, 1976)





Drawing on the ***Safe Design Theorem*** Heyman did not attempt to model the ‘actual’ stress distributions

Summing up on modelling

• Even with unlimited analytical power the uncertainties are so great that our ability to calculate the "actual state" in a building structure and underlying ground ground is unlikely to improve much, if at all.

• In most cases the real value of modelling is to place bounds on likely overall behaviour and to explore possible mechanisms of behaviour.

• Understanding the basic mechanisms of behaviour and beneficially modifying them to achieve *fitness for purpose* must be the key goal. **Understanding the ductility and robustness is an essential part of this process.**

Some examples of the application of ductility in Foundation Engineering

All foundations have stress concentrations at the edges

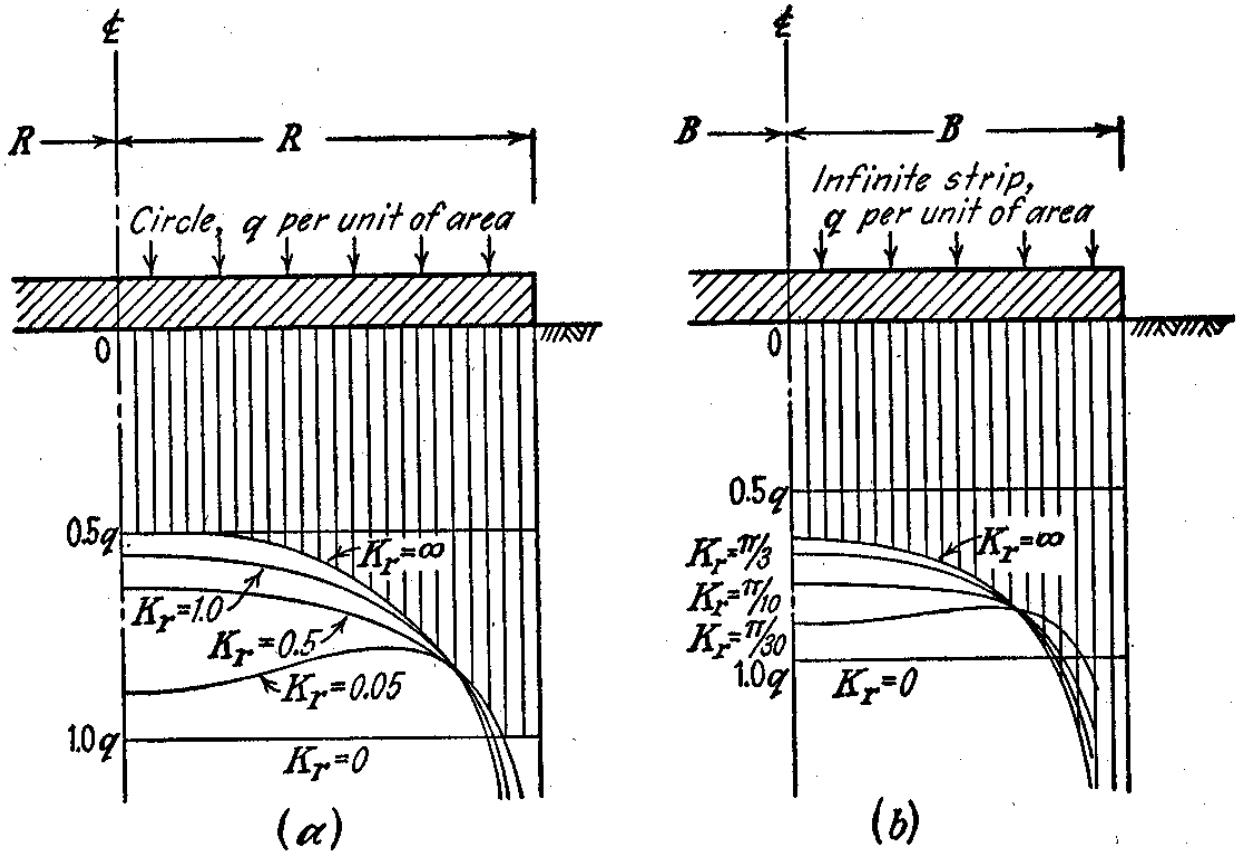
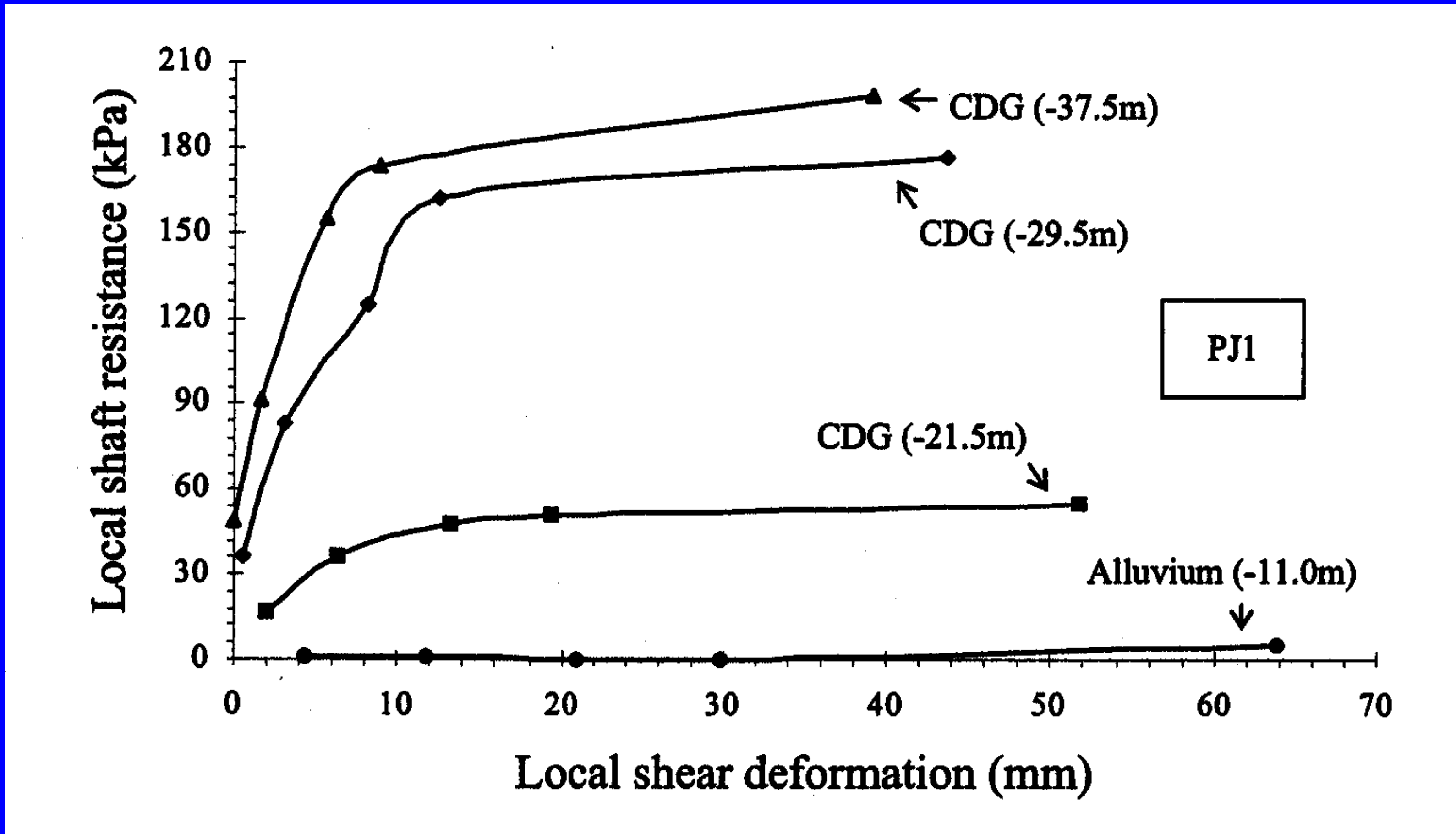


FIG. 125. (*a*) Contact pressure on base of uniformly loaded, circular plate with different degrees of flexural rigidity; (*b*) as before, for load applied on a strip. (*After Borowicka 1936 and 1938.*)

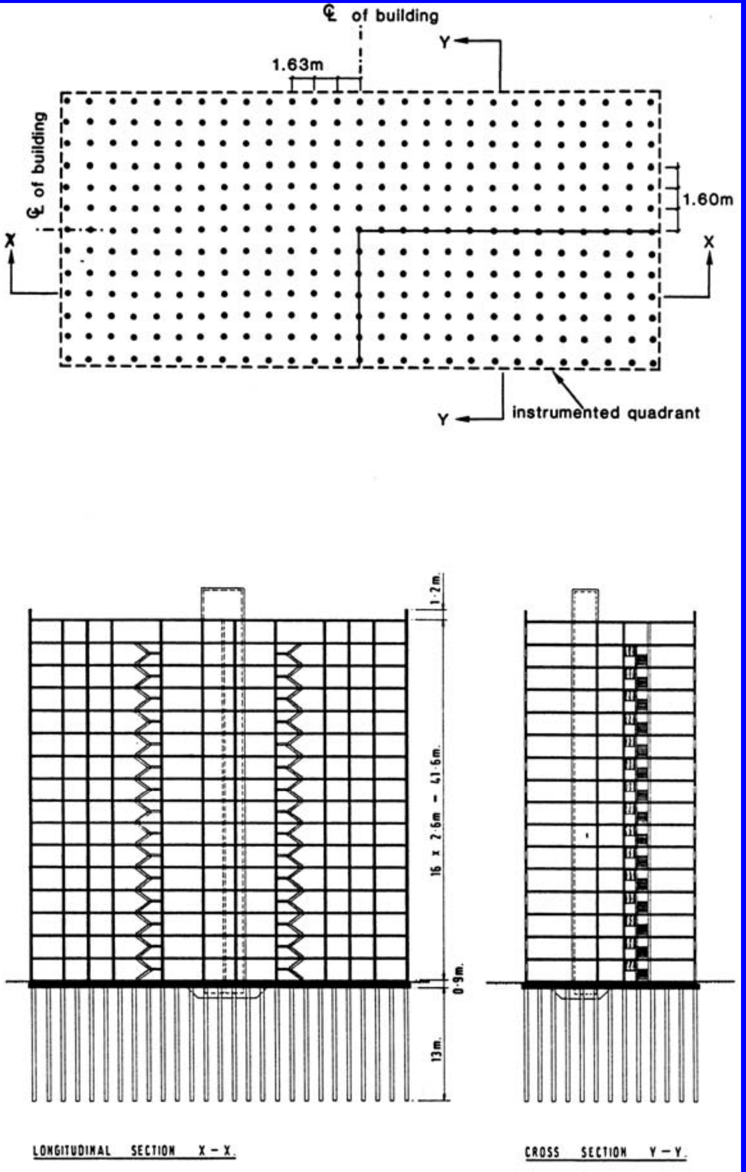
The load-settlement behaviour of most piles in soil is DUCTILE

Results of Lee *et al*. (2004) - jacked H-piles in CDG



Computer programs for Pile Group Analysis

- These are now widely available for pile group analysis - They output the vertical forces in each pile.
- <u>As for footings, the piles at the edges are usually computed to be carrying much higher loads than the centre piles.</u>
- Unfortunately some regulatory authorities, including Hong Kong, have required that each pile should individually satisfy the traditional factor of safety previously reserved for the pile group as a whole.
- This has led to grossly conservative and expensive foundations.



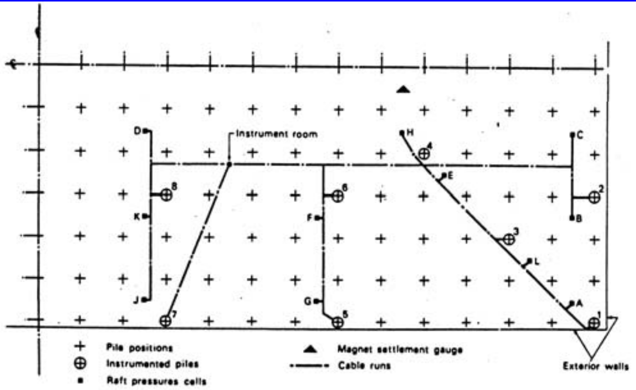
Plan and elevations of Stonebridge Park flats (Cooke *et al.*, 1981)

Block of flats at Stonebridge Park

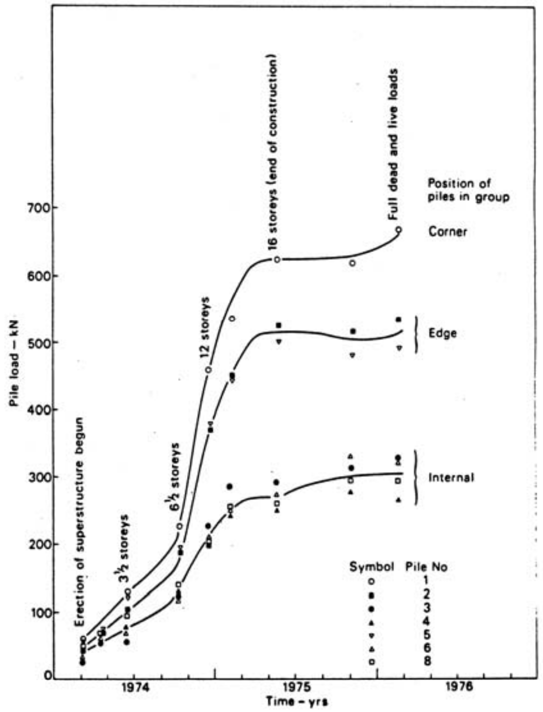
315 piles; 0.45m dia.; 13m long; observed settlement = 25mm

(Cooke *et al*, 1981)

Block of flats at Stonebridge Park



Foundation plan of north-east quarter showing positions of instruments and cable runs



Development of pile loading during erection of the building, showing the differences between the loads carried by the various characteristic piles

Measurements show that the corner and edge piles carry about twice the loads of the internal piles

23% of the total load is carried by the raft

- In the 1980s, when these programs first became available, some UK Road Construction Units adopted this approach.
- When it was found that the cost of bridge foundations had more than doubled the approach was quickly dropped.
- The traditional approach has been to apply a factor of safety to the pile group as a whole - this is nothing more nor less than the application of the ***Safe Design Theorem.***
- If a single pile approaches its full carrying capacity, its stiffness reduces and load is re-distributed to the adjacent piles. The pile continues to carry its load due to its **ductility.**

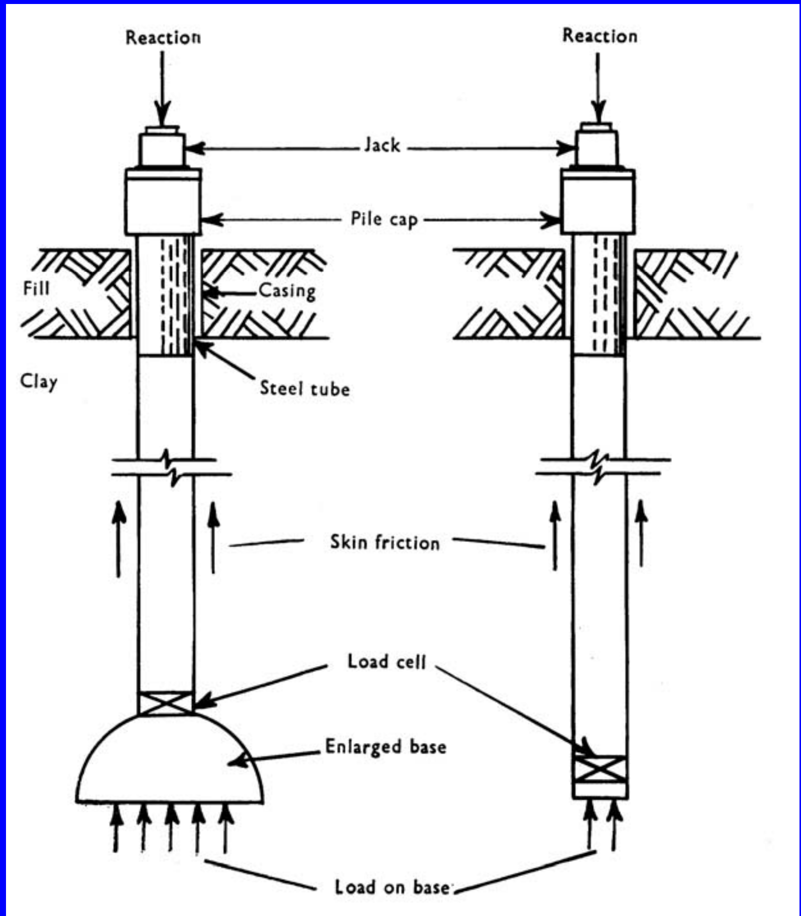
  (*In some circumstances ductility of the pile cannot be assumed)*

  (Note that local factors of safety are not usually applied to stress concentrations beneath a footing - these are simply permitted to redistribute)

Application of pile ductility in design

- Two examples of the direct use of pile ductility in design:
  - Undereamed bored piles in stiff clay
  - Stress reducing piles

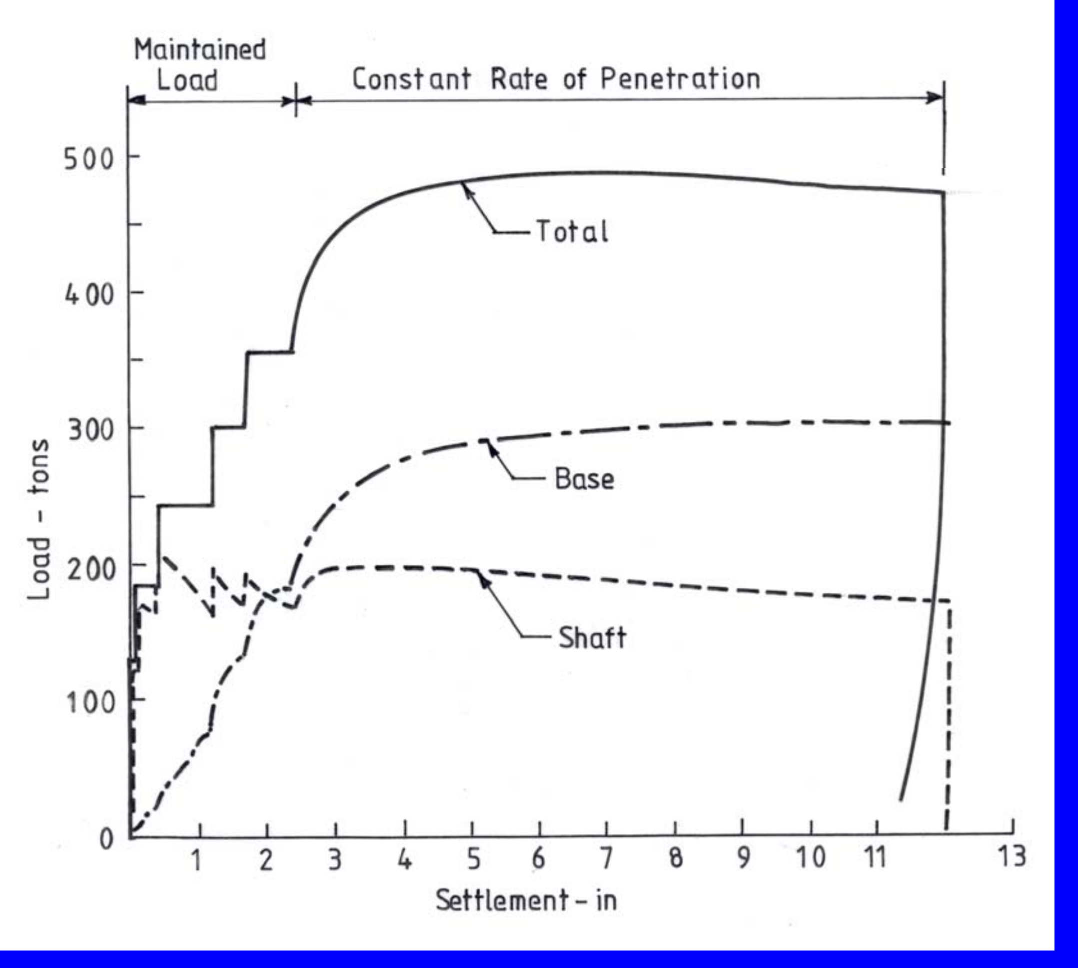
Research by Whitaker and Cooke (1966) on bored piles in stiff clay



Position of load cells in test piles

Pile base load cell

Under-reamed bored pile in stiff clay

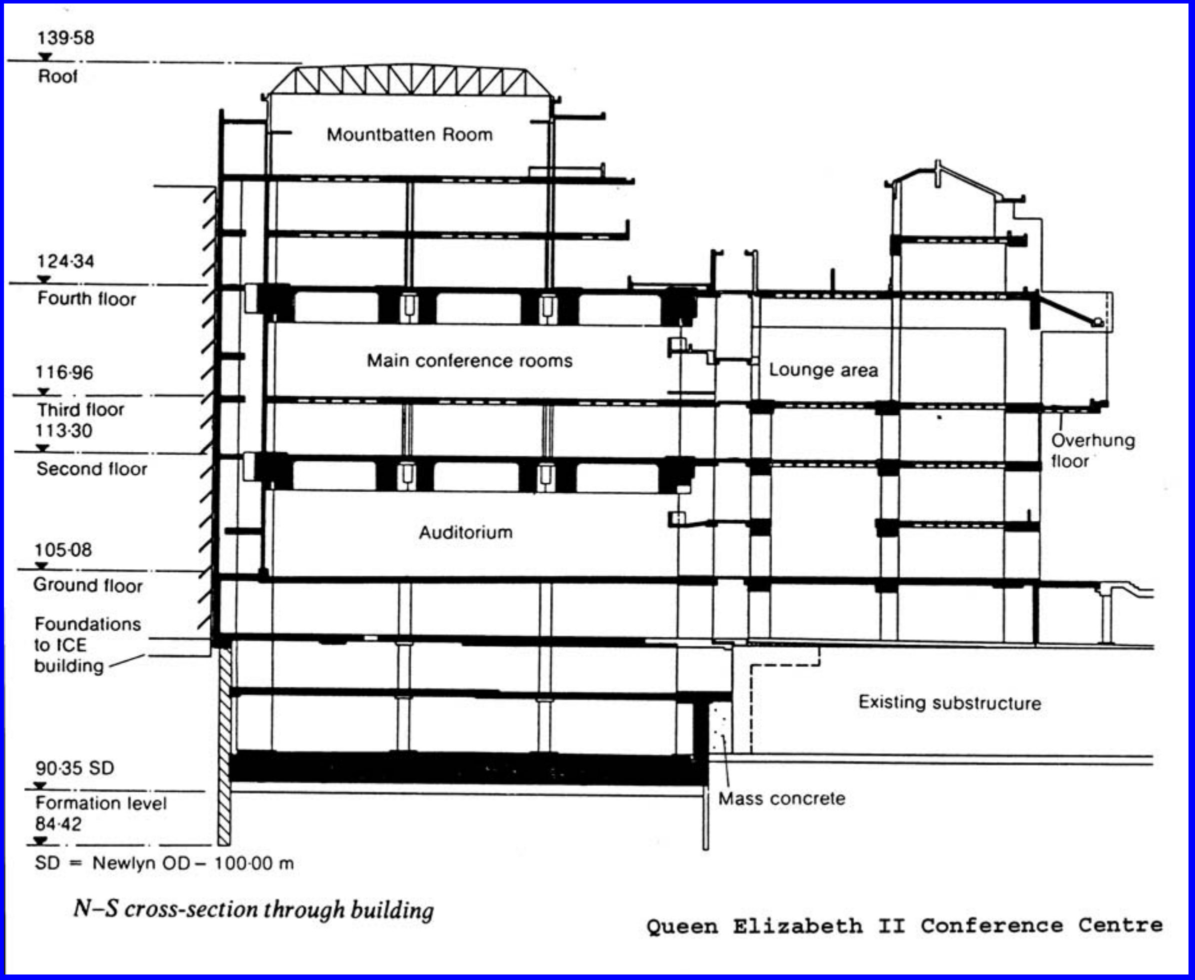


For the base to operate efficiently the shaft will be fully mobilised under working load

Stress reducing piles

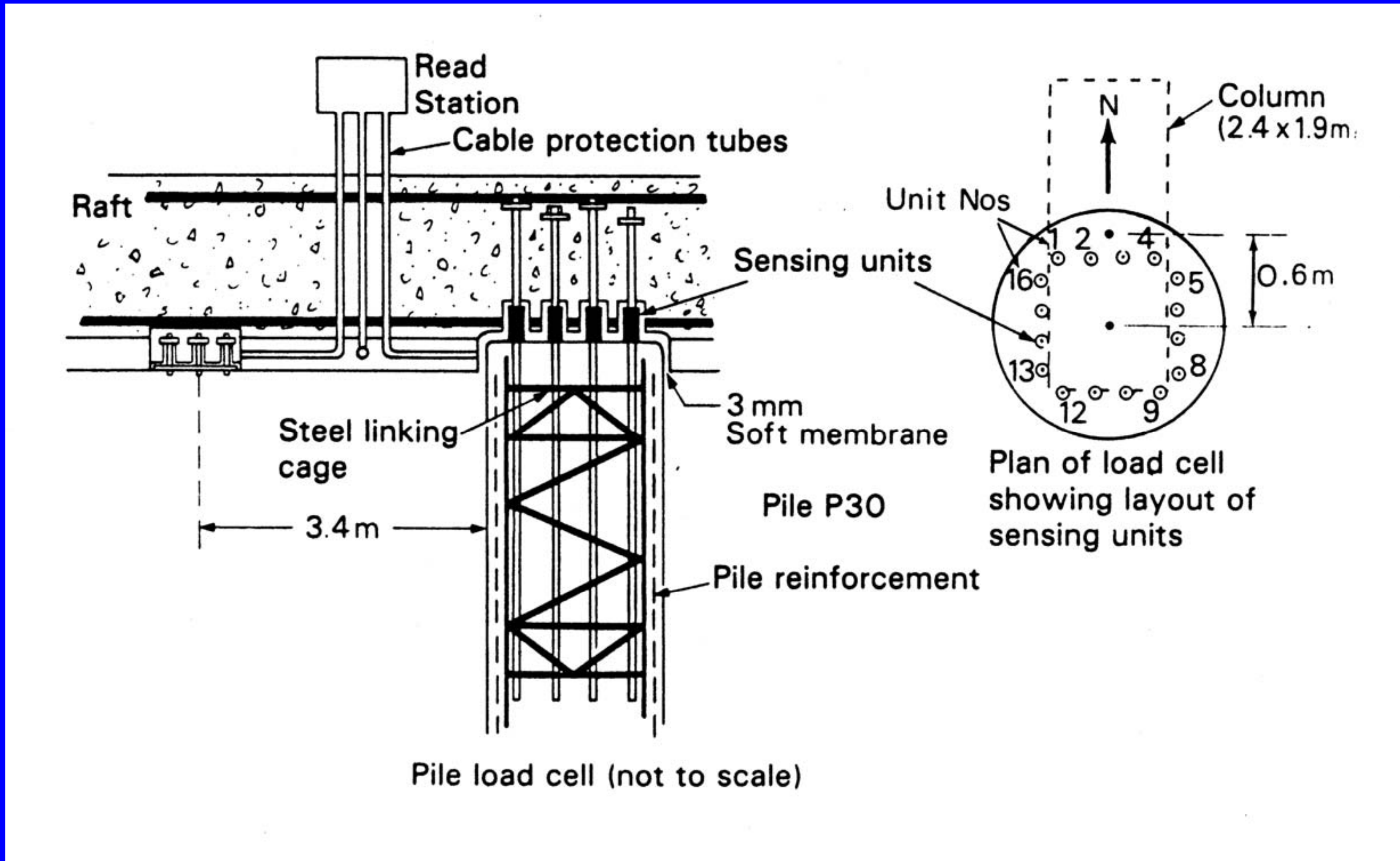
Burland and Kalra (1986)

Queen Elizabeth II Conference Centre



North-South Cross Section

QE II Conference Centre



Details of load-cells

QE II Conference Centre

Top of pile reinforcement - threaded

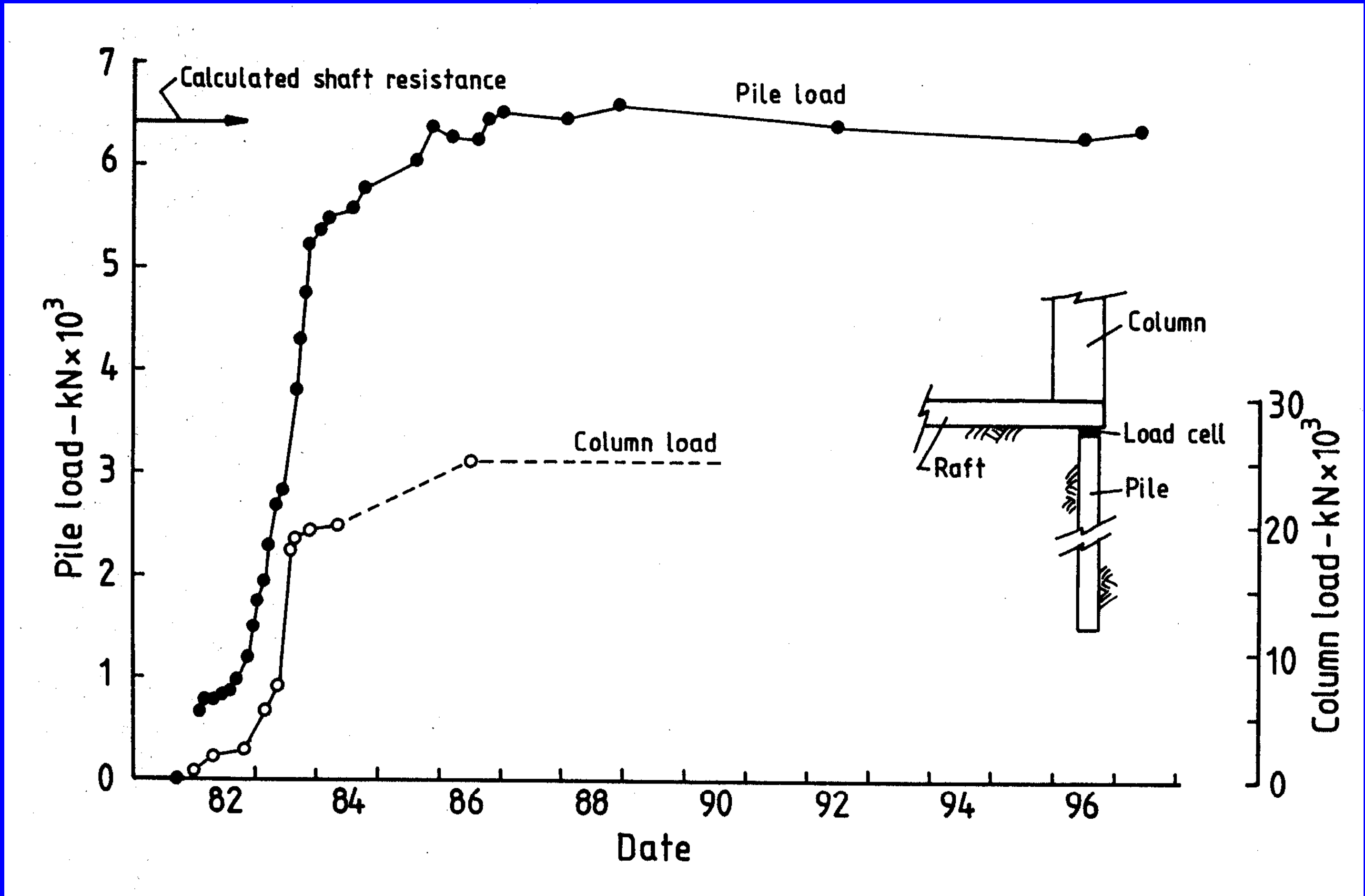
QE II Conference Centre

Load cell complete and connected to starter bars

QE II Conference Centre

Raft reinforcement being placed

Stress reducing piles - QE II Conference Centre, London



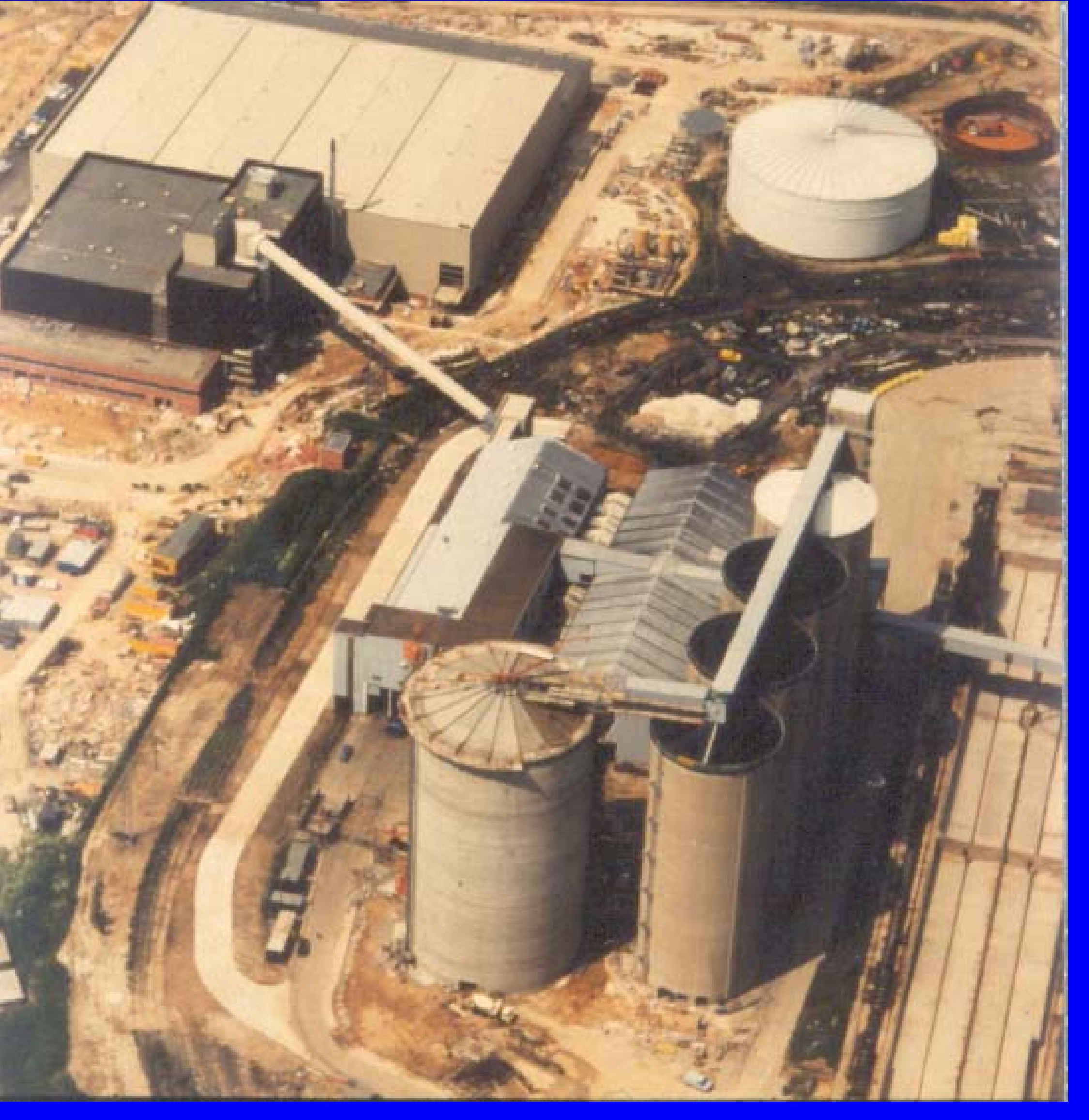
To avoid thickening the raft locally beneath the heavy columns, straight shafted piles were installed, designed to fully mobilise

Two puzzling case histories for which understanding the mechanisms of behaviour proved crucial

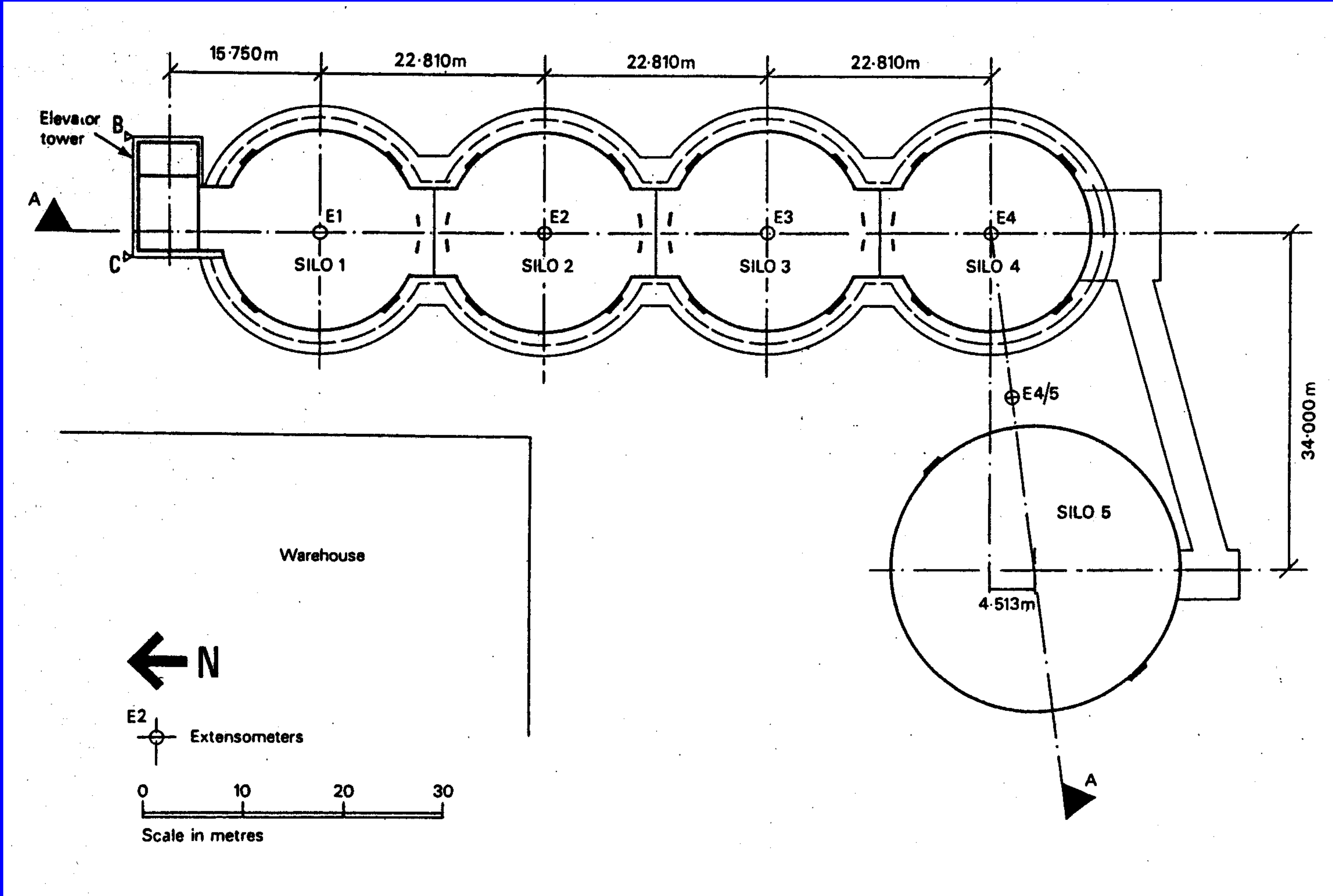
A Case History of the Failure of some silos during discharge
(due to soil-structure interaction?)

Silos 1 to 4 built in 1973

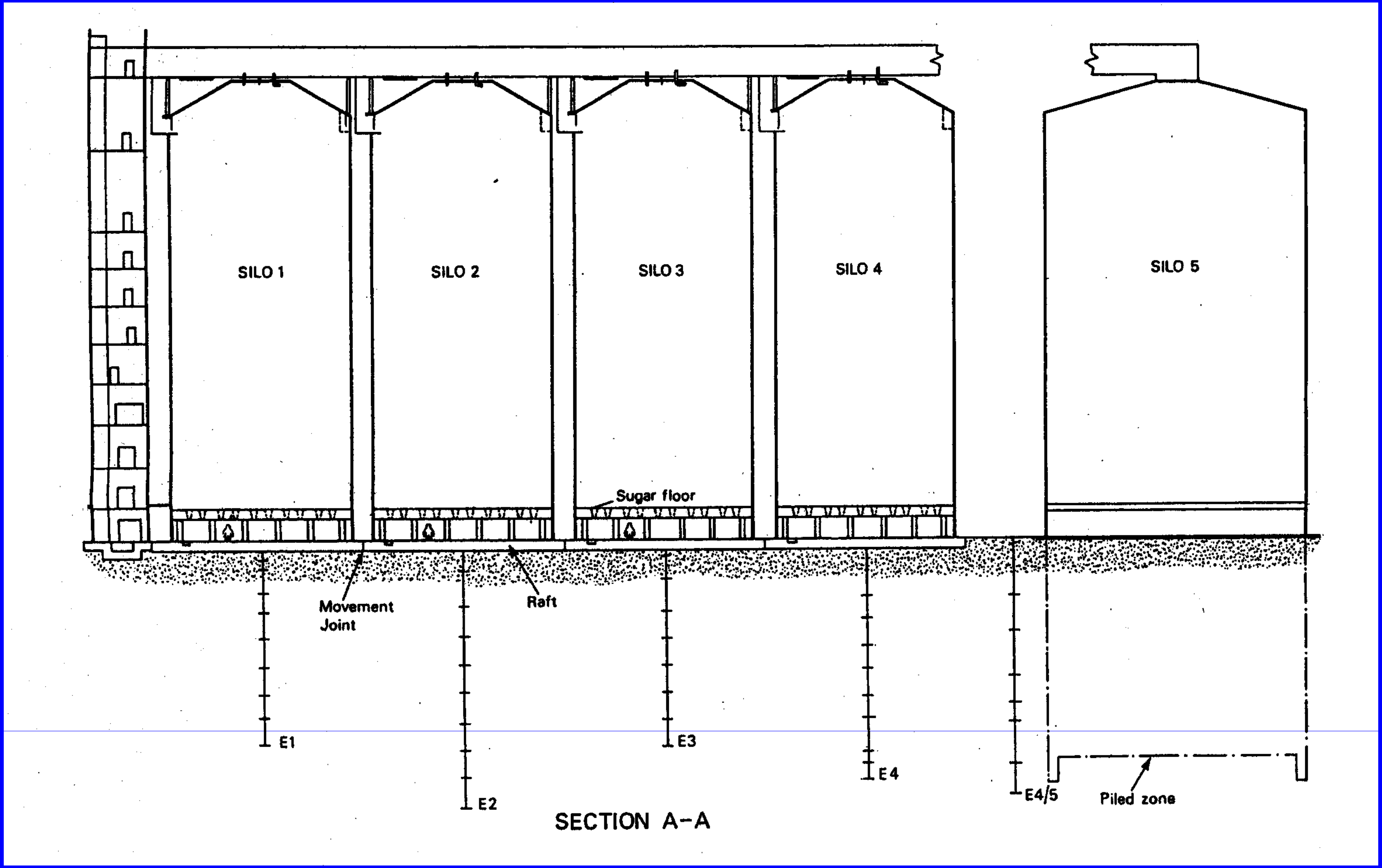
Silo 5 added in 1982



Plan view of Silos



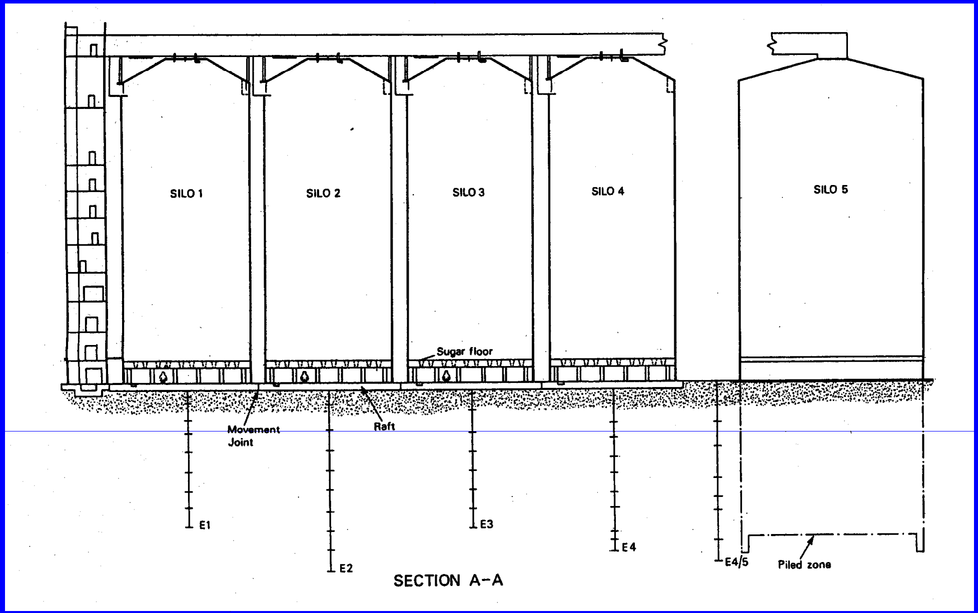
Vertical section through silos 1 to 5



Silos 4 and then 3 failed during discharge after the first loading of Silo 5

Professor Rowe (1995) attributed the cause of the failure to interaction between the foundations of Silo 5 and Silos 3 & 4

"Causation was traced to the unexpectedly high stiffness of the stored material in reaction even to minimal distortions of the walls imposed from an exterior source".



Precision levelling points around the walls and on the columns.

Magnet extensometers.

Top of b/h 4/5 settled 3.2mm during first loading. Little vertical straining of ground over depth of piles - effectiveness of sleeving.

Silo 4 inclined towards Silo 5 by about 2mm across raft and the centre settled by 3.4mm

Silo 3 showed no inclination and settled by less than 1mm

No measureable out of plane distortions around bases of silos

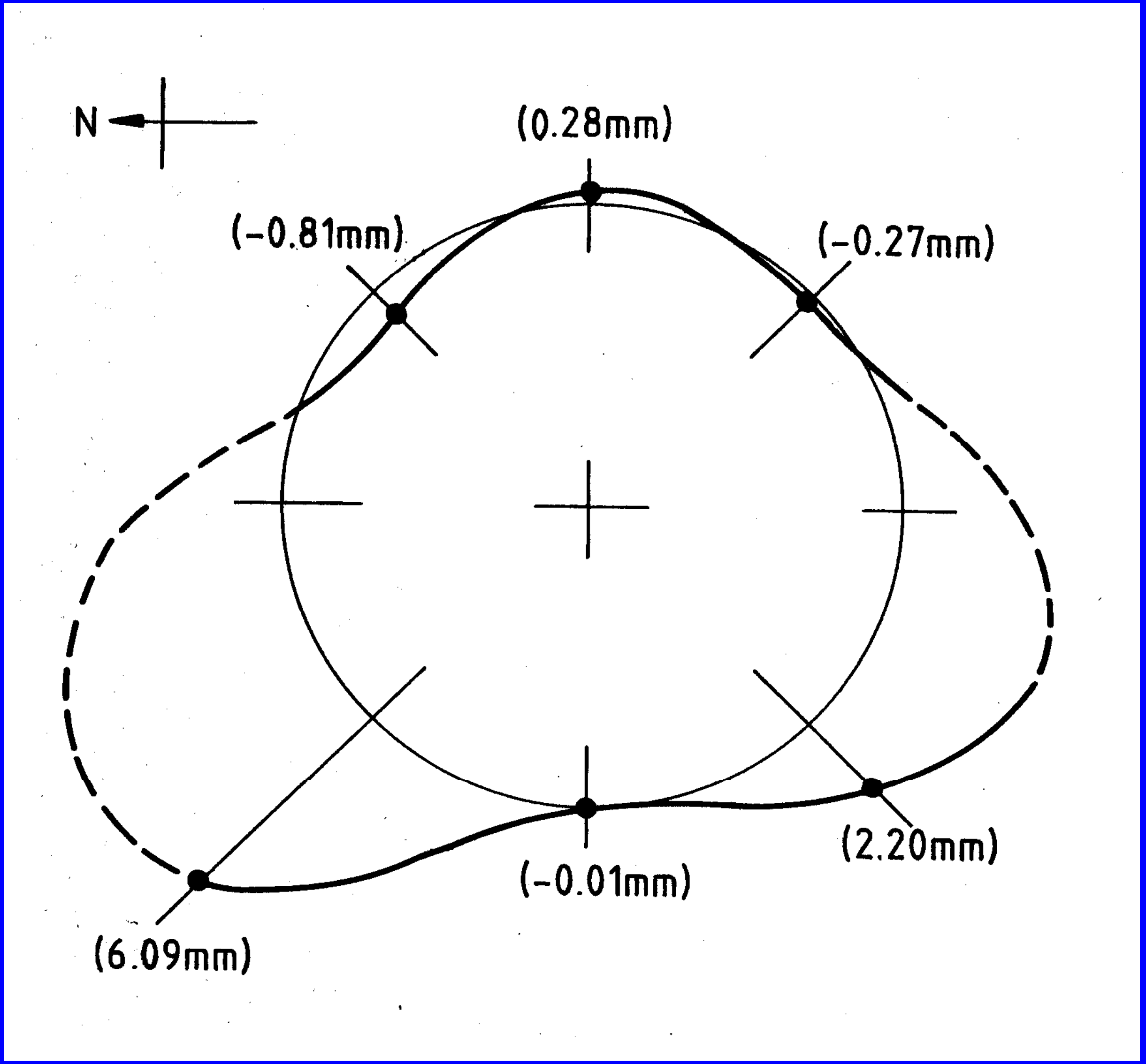
THE INDUCED MOVEMENTS WERE EXTREMELY SMALL

During the previous operation of Silos 1 to 4 there had been significant interaction between them with induced settlements of up 20mm. But they had performed very satisfactorily

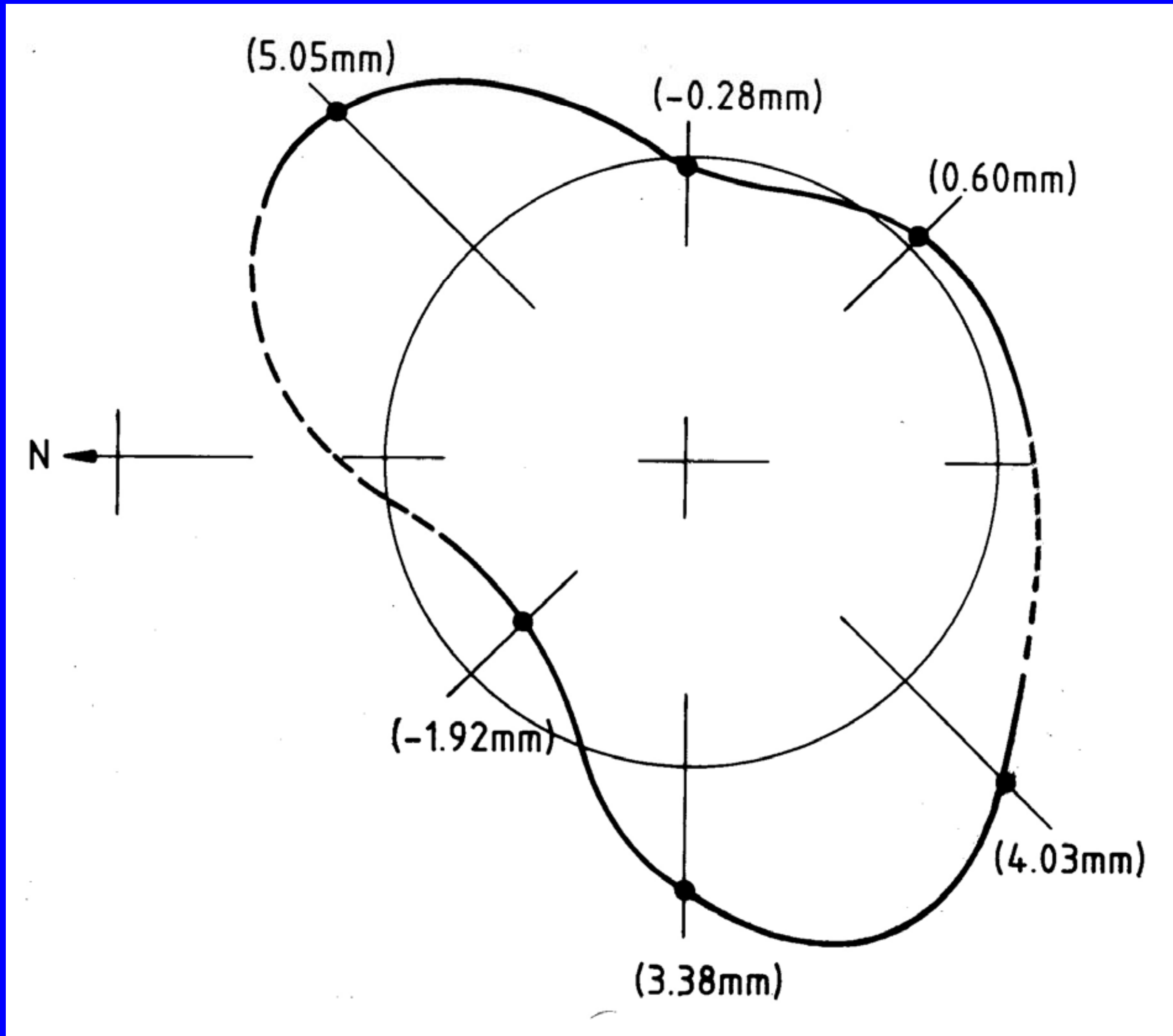
A key question is:
"*Why should such small movements induced by loading Silo 5 have triggered the failure of Silos 3 and 4 on commencement of unloading when in the past much larger interactions had safely occurred*"?

The form of the foundation movements that took place during unloading are crucial in attempting to answer this question

Silo 3: Vertical displacements around base when unloaded from 12,133t to 11,098t



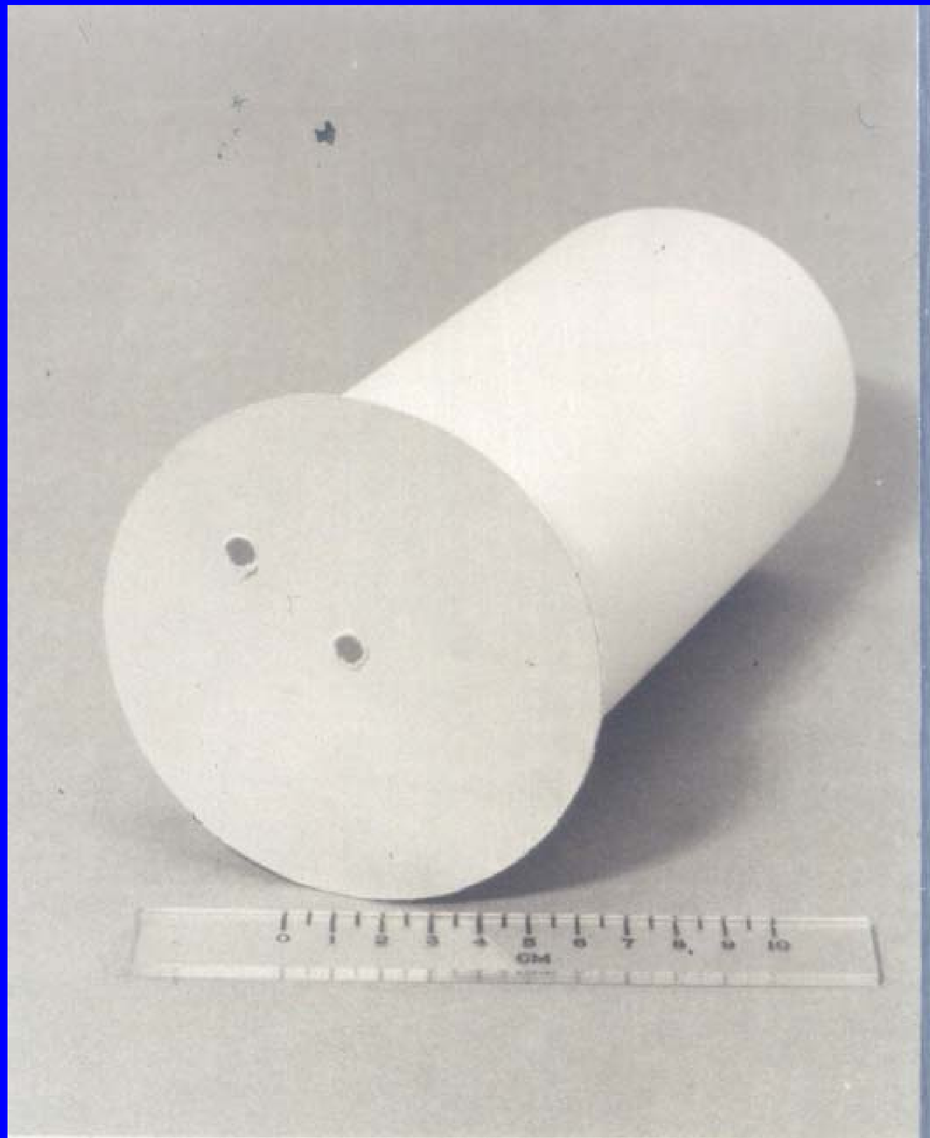
Silo 4: Vertical displacement around base when unloading from 12,133t to 11.098t



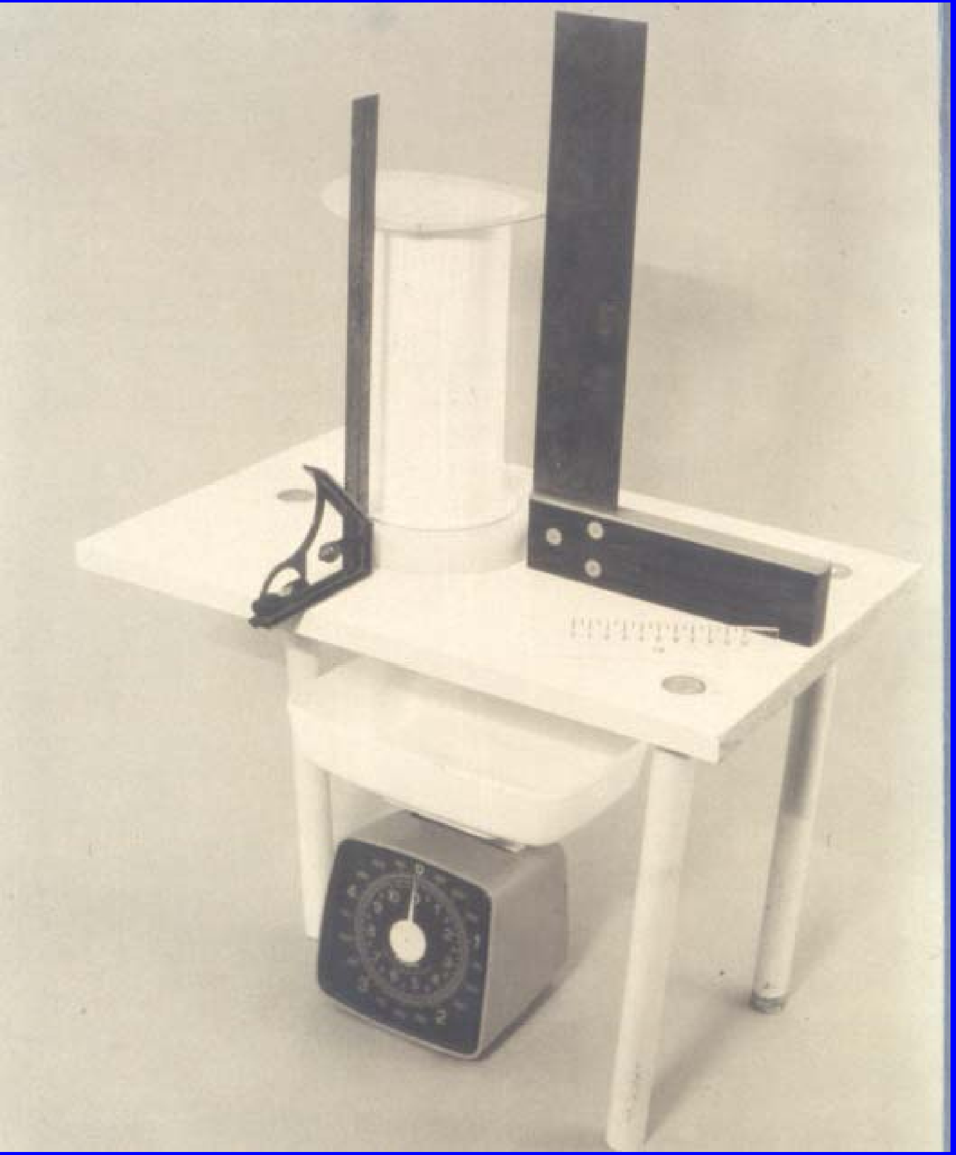
The form of foundation movements were intriguing

- The shapes are different from an expected subsidence trough.
- A vertical cylinder is very stiff when subjected to differential vertical forces around its base. Could such large distortions really have resulted from vertical forces coming up from the underlying ground?
- However the same cylinder is very flexible when subjected to non-uniform internal radial pressures.
- I undertook some simple model tests to explore the effects of eccentric internal vertical flow during discharge

Model paper silo showing discharge holes in cardboard base

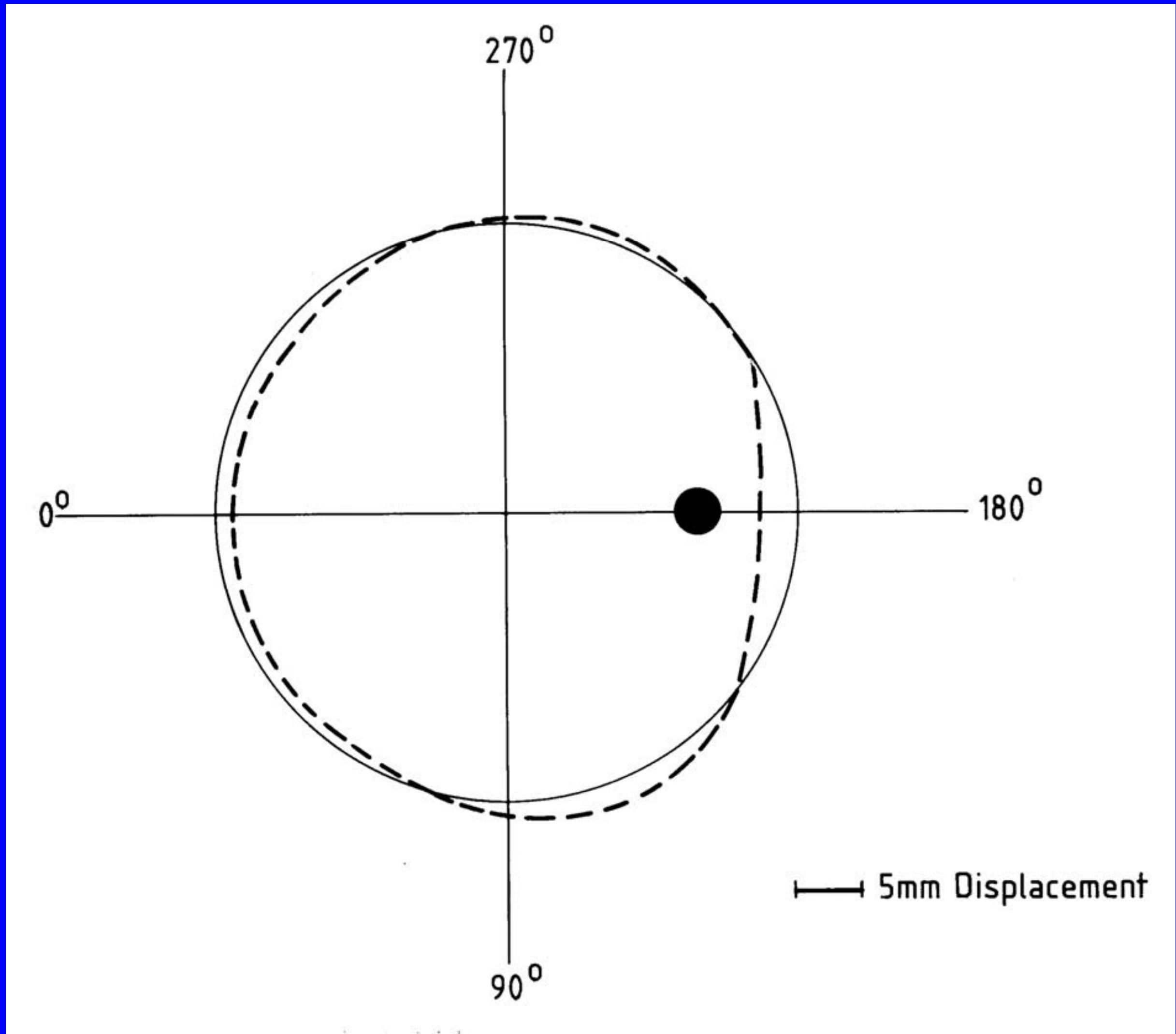


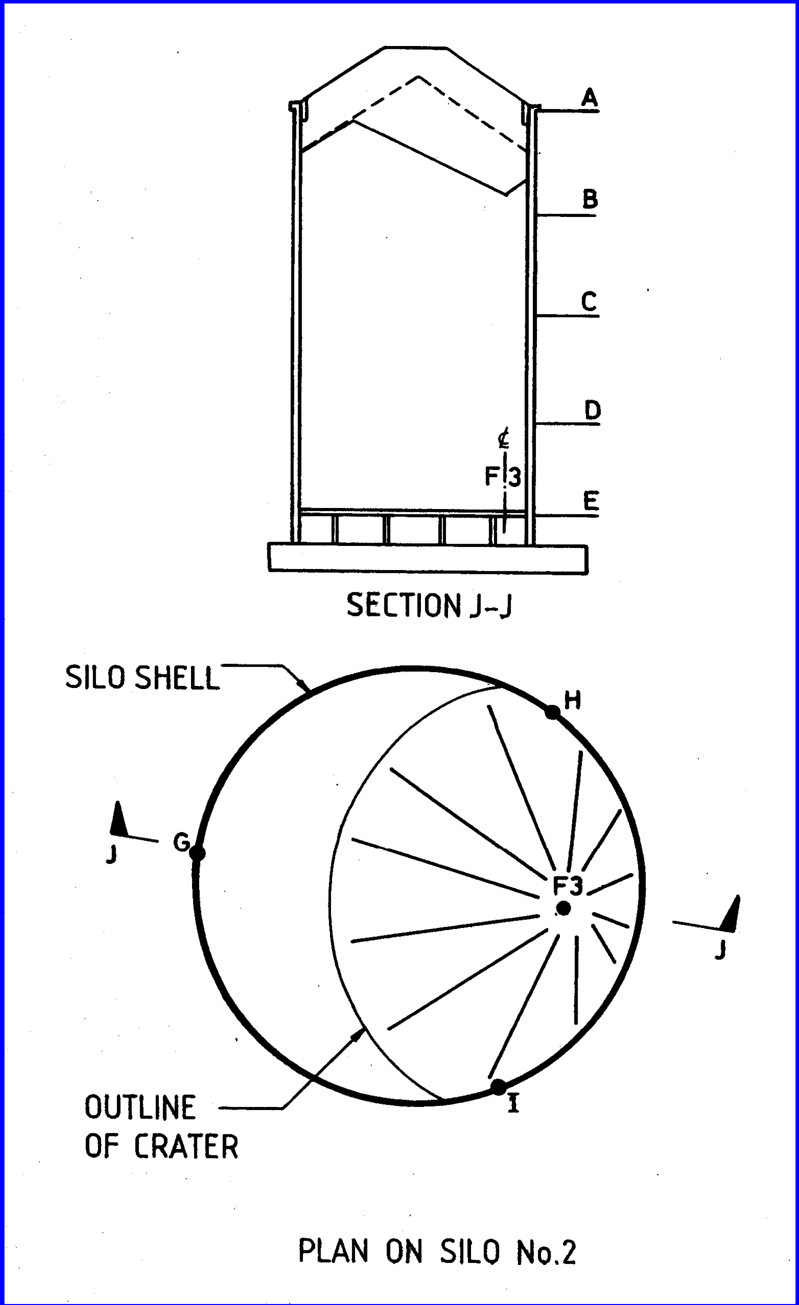
Model silo on foam rubber foundation, note transparent screen on top of silo



Loading model silo – note temporary former

Paper silo: radial displacements at top due to 10 percent eccentric discharge from 2/3 radius





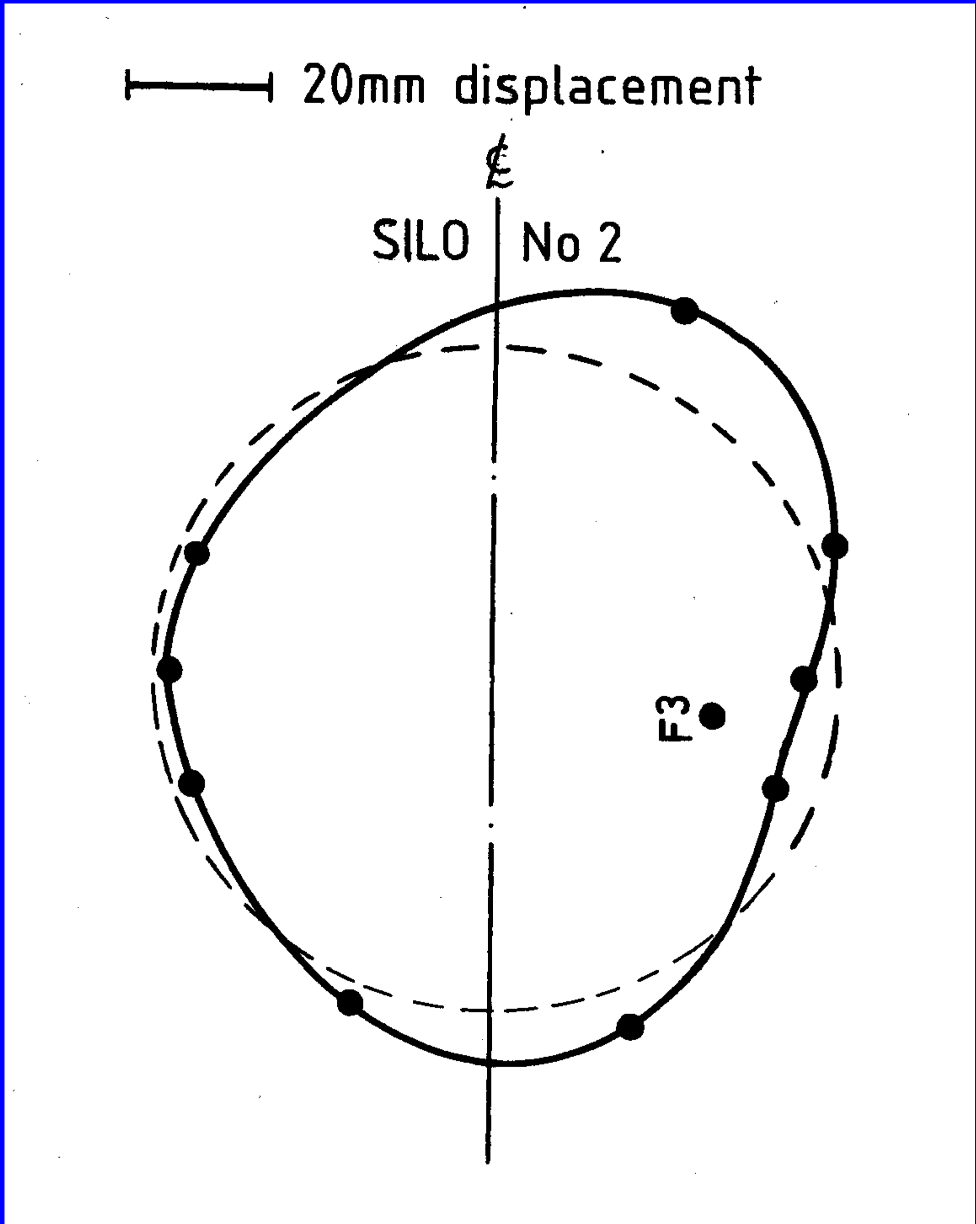
Full-scale eccentric discharge tests at Felsted

(Driver and Dawson, 1988)

Radial displacements measured at various elevations - note elevation C

Content reduced from 12,000t to 10,778t at 2/3r eccentricity

Profile of content after 10% discharge



Felsted full-scale trial.

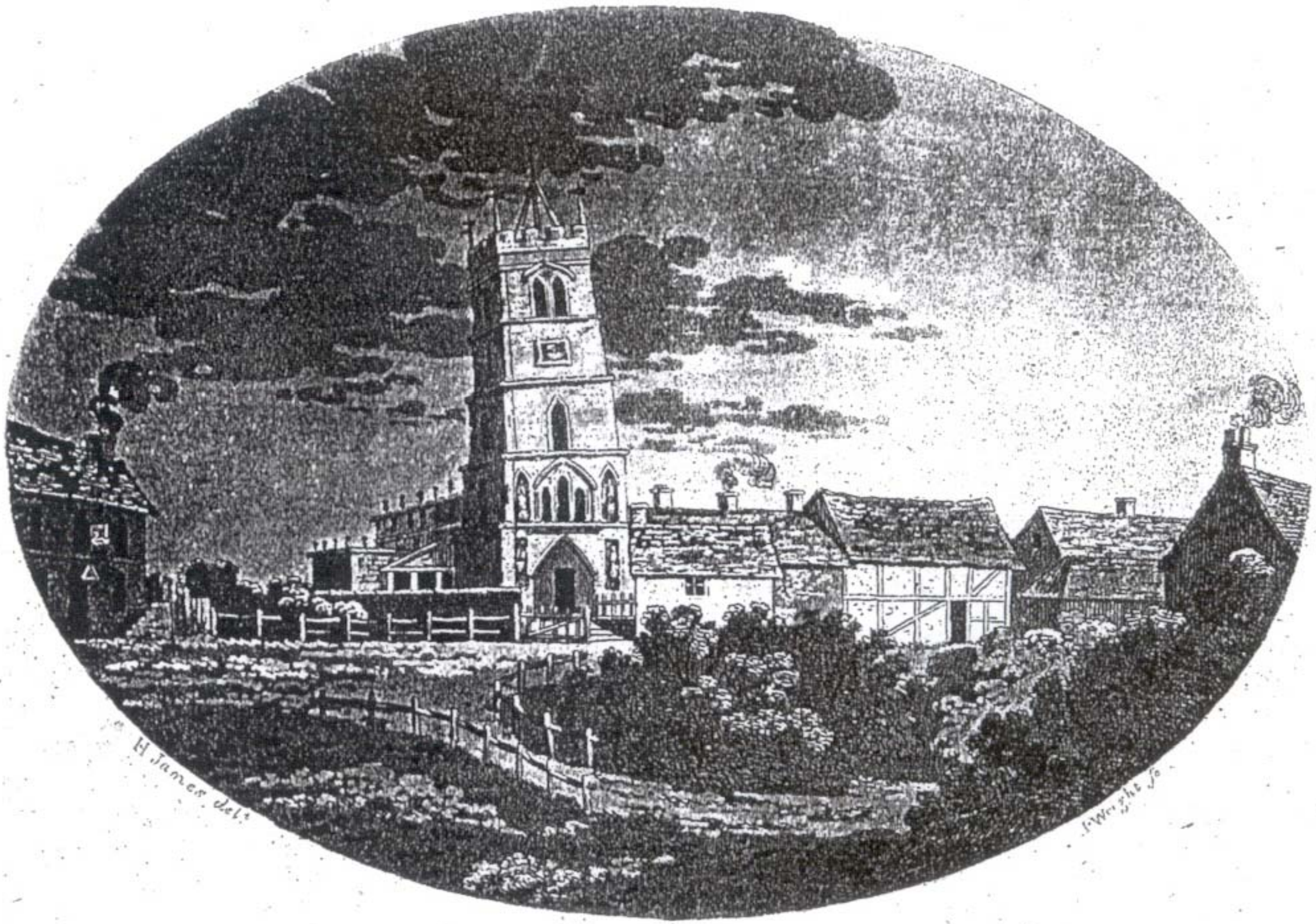
Measured radial movements at level C for eccentric discharge at 2/3 radius
(Driver and Dawson, 1988)

An Historical Enigma

The stabilisation of the 15th century tower of St Chad, in Wybunbury, by James Trubshaw in 1832


WYBUNBURY SHOWING MOATED SITES 1975

The Hanging Steeple of Wybunbury



HANGING STEEPLE at WYBUNBURY.

In the Possession of Mr Yoxall, —

1751

"The spire of a church which had deviated from the perpendicular 5ft 11in., and was split several inches apart a long way up the centre, has lately been set straight by Mr Trubshaw."

Architectural Magazine, 1834

“Mr Trubshaw, …... proceeded to bore a row of auger-holes clear through under the foundations of the high side…...

These holes he filled with water; and, corking them up with a piece of marl, let them rest for the night.

……….the building gradually began to sink, another row of holes was bored, but, not exactly so far as the first row.

…...the high side not only kept sinking, but the fracture in the centre kept gradually closing up.

This process was continued till the steeple became perfectly straight, and the fracture imperceptible."

Quote from Anne Bayliss' thesis:

Trubshaw stabilised the tower without any

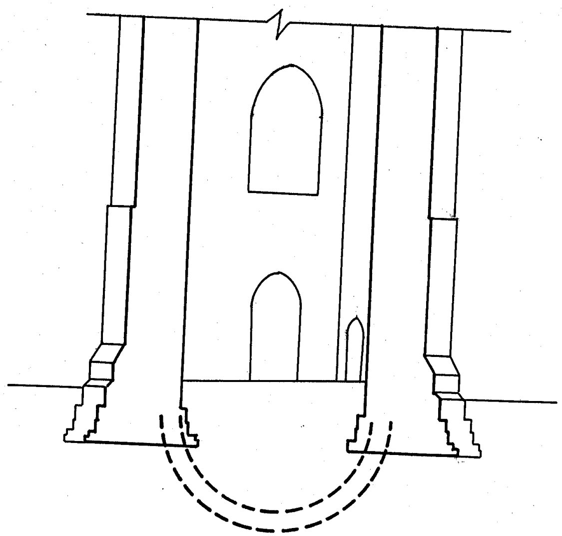
"wonderful machinery or secret inventions"

Source unknown

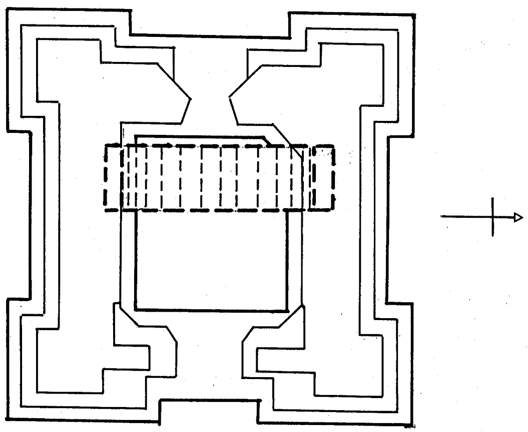
Soil Extraction at Pisa

WYBUNBURY TOWER WITH NEW FOUNDATIONS ON JACKS


OLD INVERTED ARCH FOUNDATIONS TO WYBUNBUR



Vertical Section looking West



Plan of Foundations

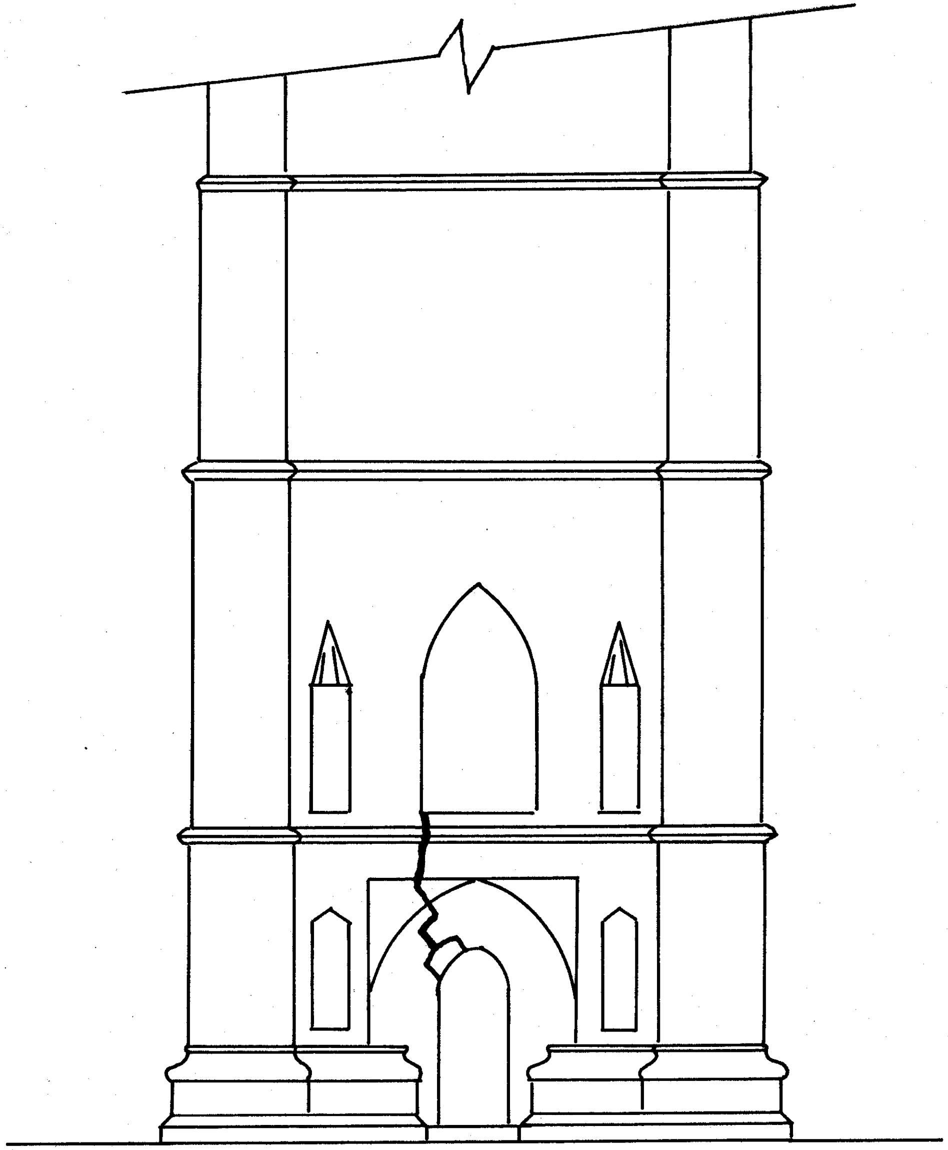
Elevation and plan showing Trubshaw's semi-circular inverted arch beneath the western side of the foundations

What was the function of this arch?

"…….and the high side not only kept sinking, ***but the fracture in the centre kept gradually closing up.*** *This process was continued till the steeple became perfectly straight, and the fracture imperceptible."*

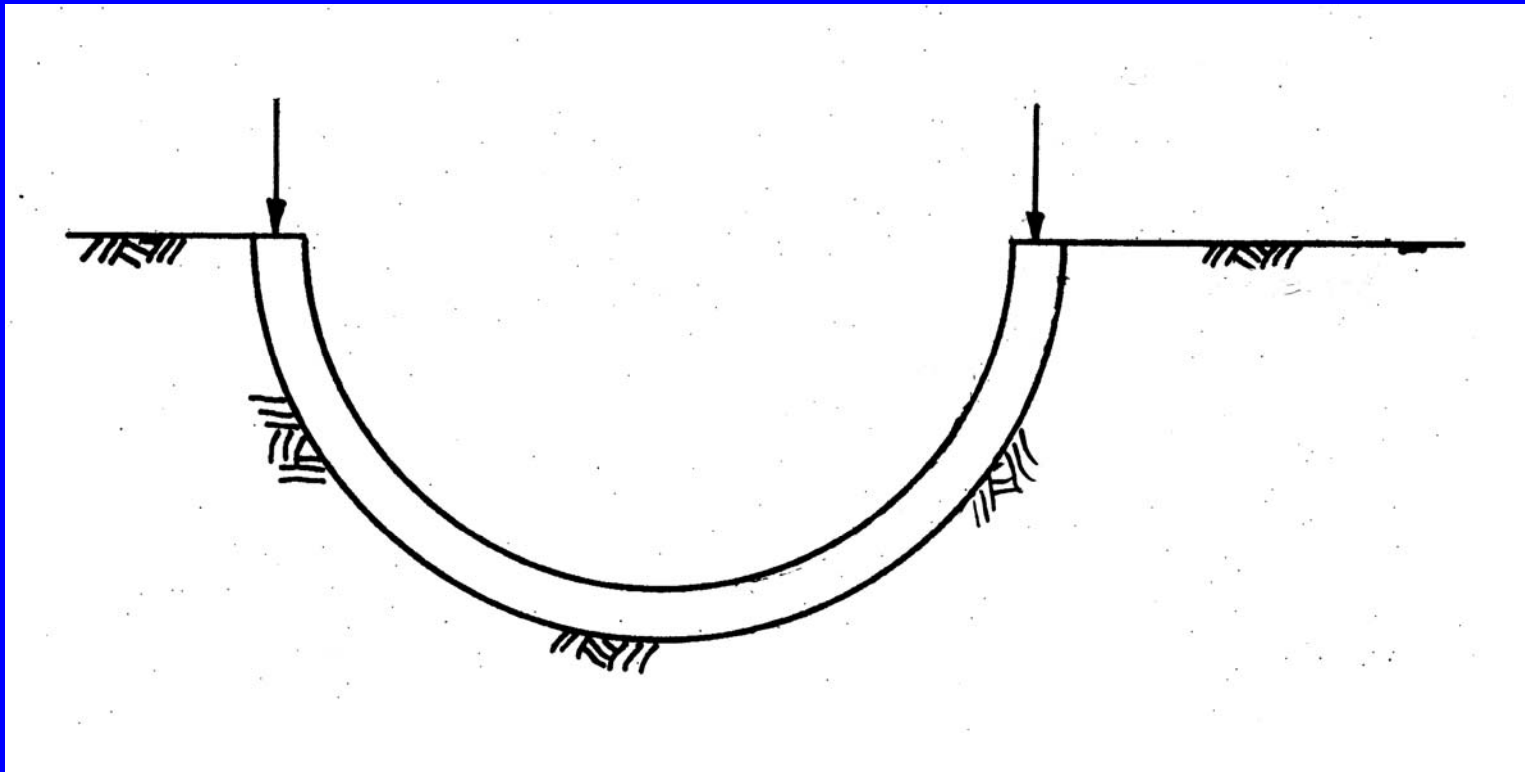
I had thought that the fracture was between the tower and the church. But we went back and examined the tower.

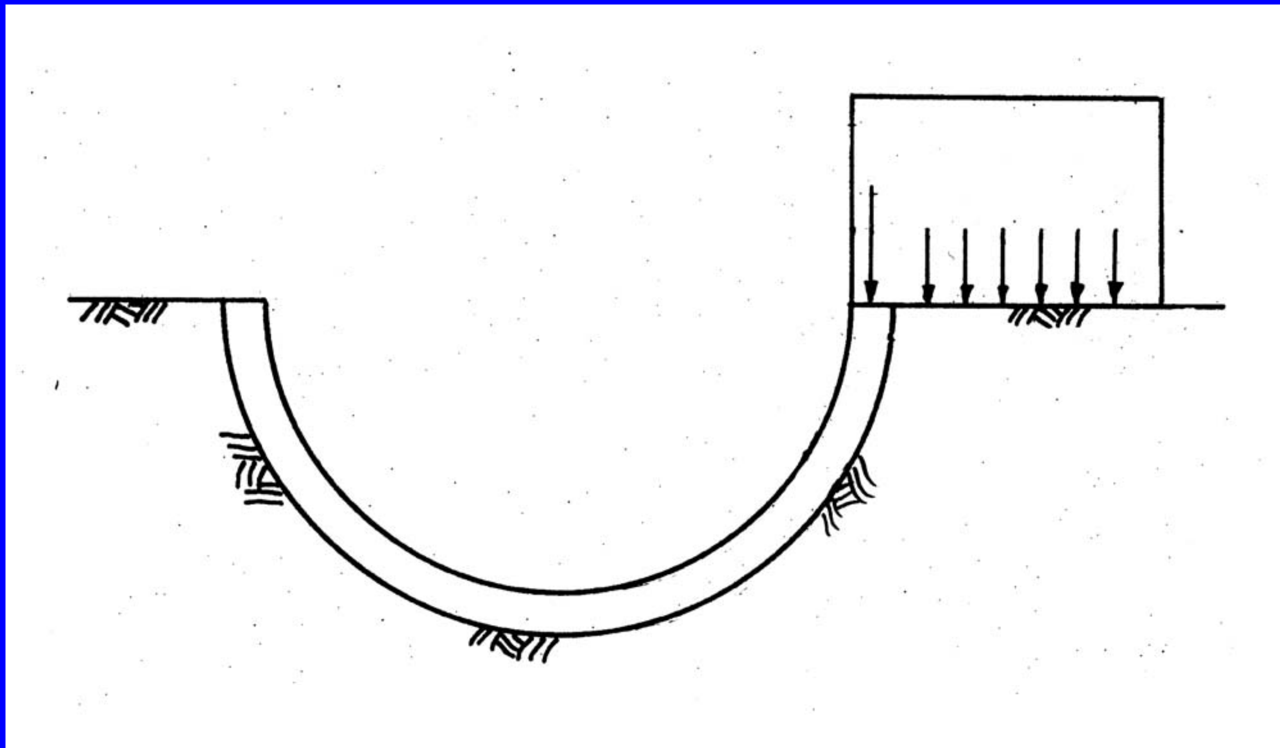
WYBUNBURY TOWER WITH NEW FOUNDATIONS ON JACKS

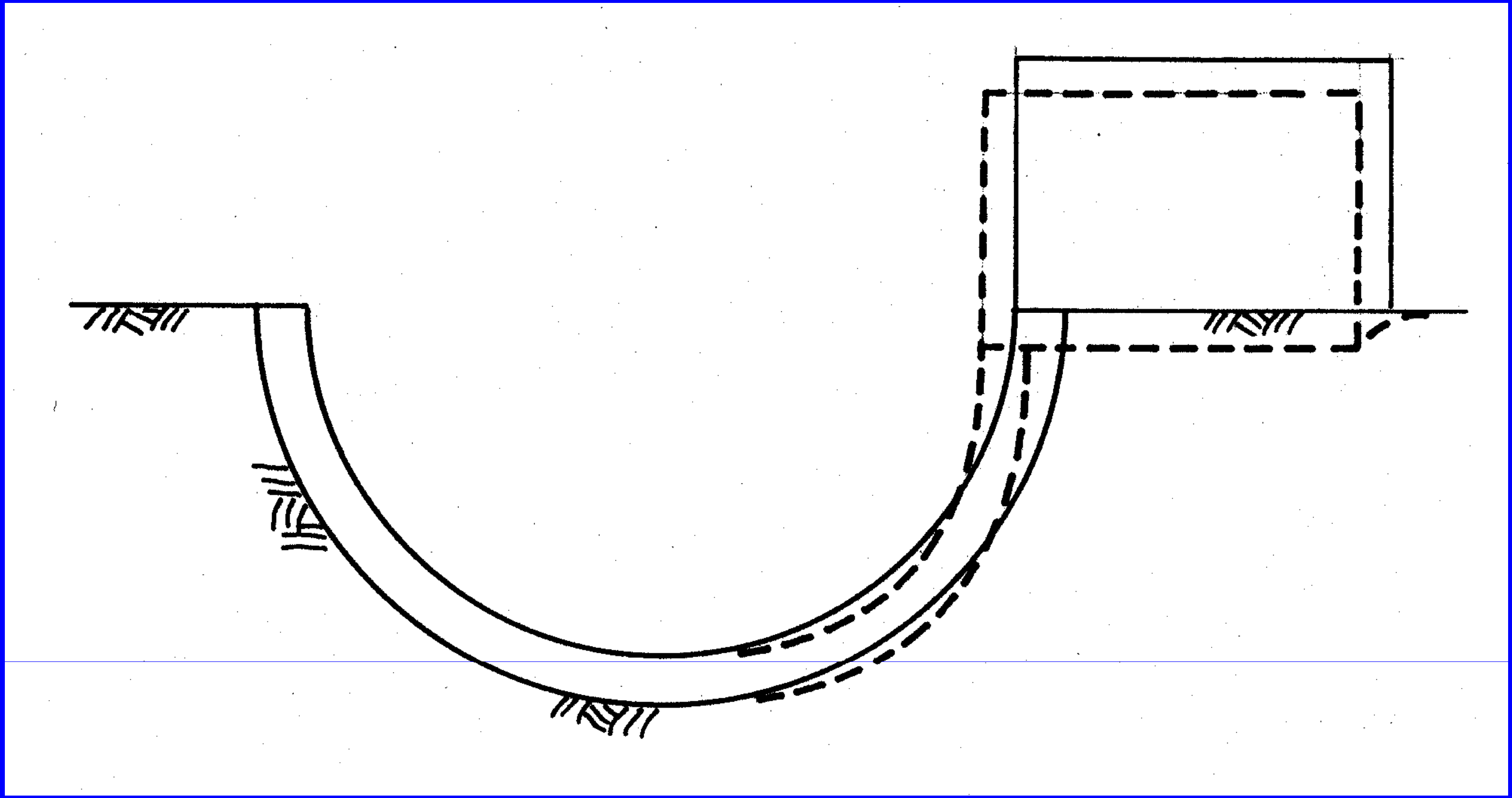


Western elevation of Tower showing:
"split several inches apart a long way up the centre"

Could the purpose of the inverted arch have been to achieve this closure of the fracture?







o Model tests using foam rubber demonstrate that, as the foundation subsides, the springing point of the inverted arch moves inwards such that the arch closes slightly.

o This action could have led to closure of the fracture in the western façade.

o Trubshaw was a most ingenious and intuitive engineer

Is it possible that he could have anticipated this behaviour?

Conclusions

- At first sight the idealisations adopted by Structural Engineers appear less uncertain than those adopted by Geotechnical Engineers.
- However, the success of structural design calculations owes more to the inherent ductility adopted in practice than it does to calculating the actual state of a building - *Safe Design Theorem.*
- Structural Engineers tend to think in terms of force and stress, Geotechnical Engineers are used to working in terms of strain and deformation.
- Structural Engineers brought up on concepts of limiting stress and "actual state" find it difficult to accept behaviour that implies full mobilisation of resistance of some of the elements.
- *Hambly's paradox* greatly aids the understanding of these ideas.

- The processes and idealisations involved in geotechnical modelling can perhaps be best understood by considering those processes and idealisation that a Structural Engineer must adopt when working on an ancient historic building - the approaches are very similar.

- Some case histories have been given illustrating the importance of ductility and robustness in designing for structure-foundation interaction.

- I have described two case histories where understanding the mechanisms of behaviour provided the key. Unless the basic mechanisms of behaviour are understood and incorporated no amount of sophisticated numerical modelling will help. Quite simple physical models can be very instructive

Concluding remarks

• Understanding and designing for ground-structure interaction requires all the traditional skills of the engineer:

• *Reliance on observation and measurement;*

• *A deep understanding of materials, both ground and structural;*

• *The development of appropriate conceptual, physical and analytical models to reveal the underlying mechanisms of behaviour;*

• *Well winnowed experience based on a discerning knowledge of precedents and case histories.*

I hope that I have shown that a balanced geotechnical triangle is a good foundation for any structure.