Development in the field of Reinforced Earth Structures

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2. **Typical examples of reinforced earth structures**
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Basic principles of soil reinforcement

timber, steel, concrete X soil (min. tensile strength)

DEVELOPMENT

mass concrete → reinforced concrete →
→ prestressed concrete → fibre-reinforced concrete

Soil → reinforced soil (macro-reinforcement) →
→ pre-stressed reinforced soil →
→ soil with randomly distributed reinforcement (micro-reinforcement)

MAIN EFFECT OF SOIL REINFORCEMENT

a) Improvement of stability, bearing capacity of earth structure

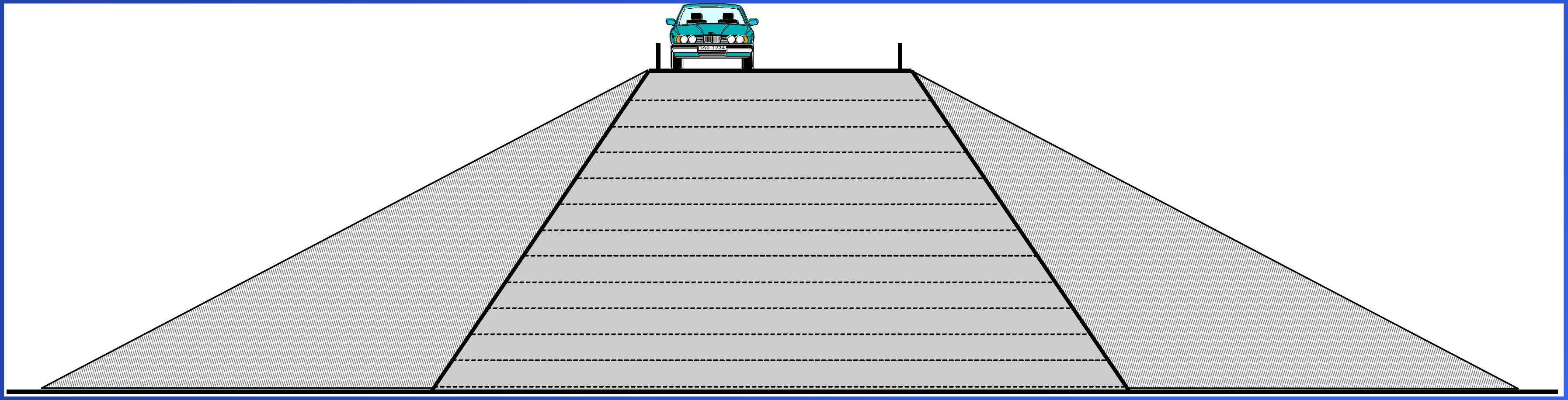
- shear plane passing through reinforcement zone
- shear plane outside of reinforcement - cinematically more demanding

b) Reduction of total and differential settlement

- stiffness of reinforcement
- involvement of large part of earth structure on load transfer

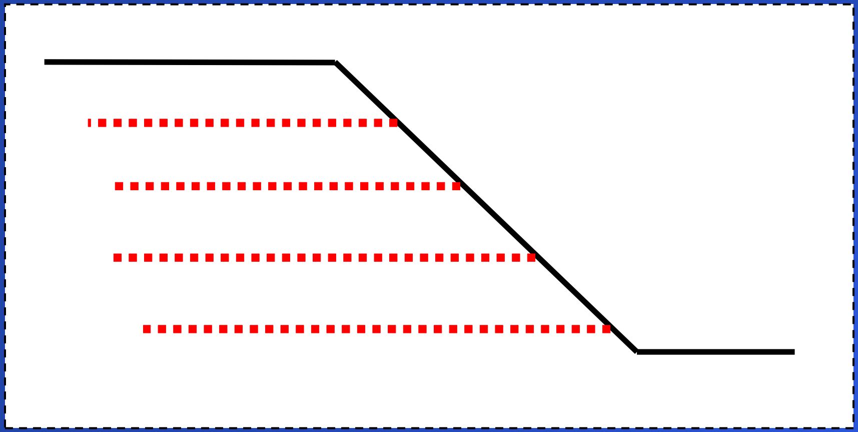
Typical examples of reinforced earth structures

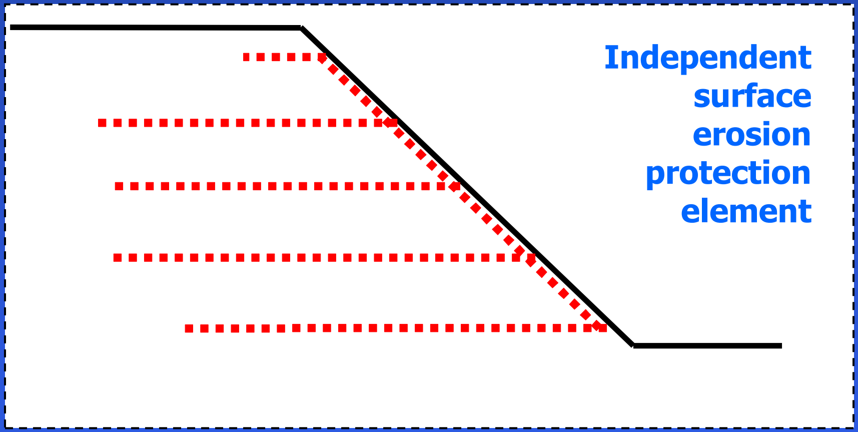
- Transport engineering

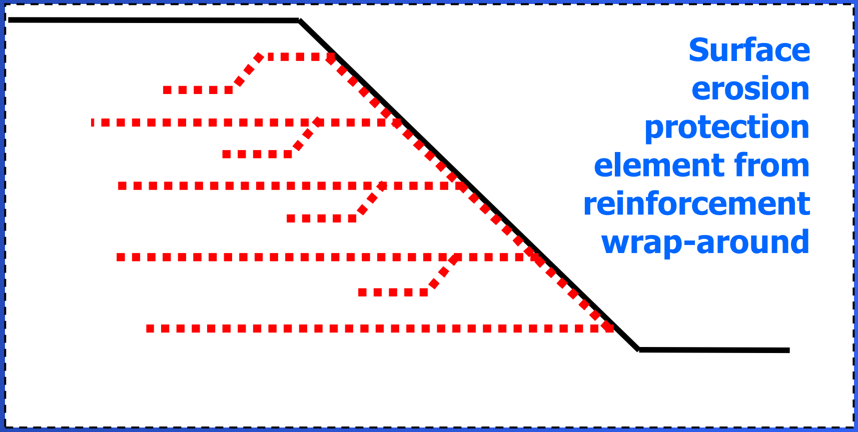


Comparison of unreinforced and reinforced fill

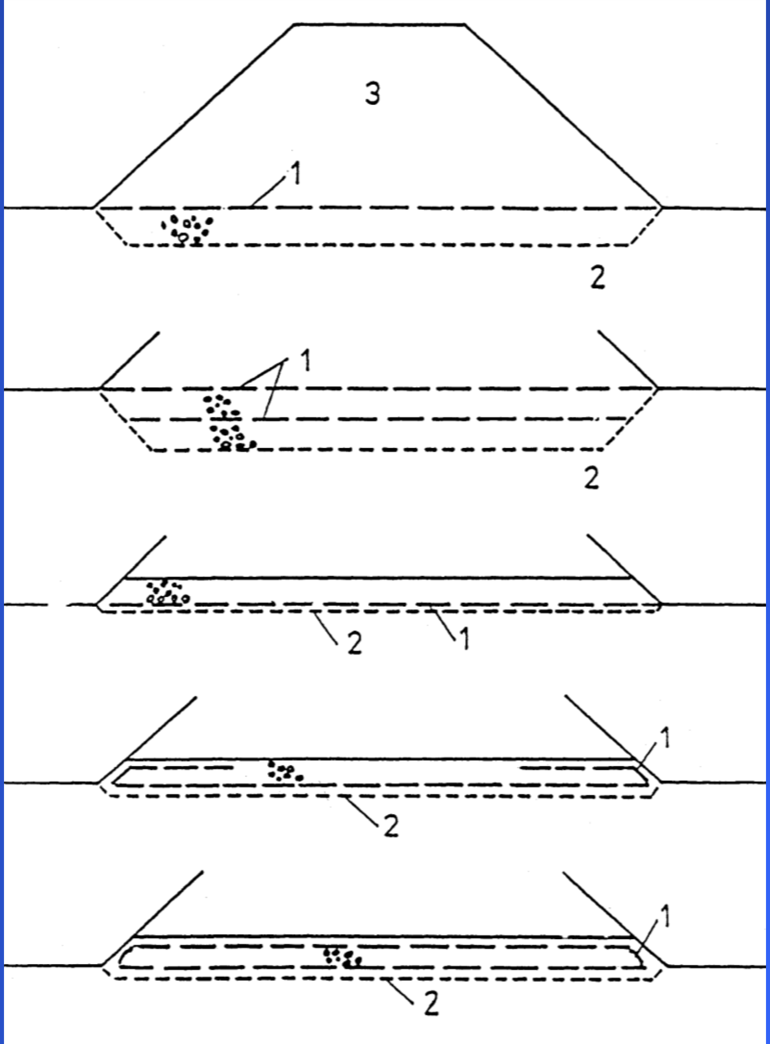
Reinforced slope – facing options



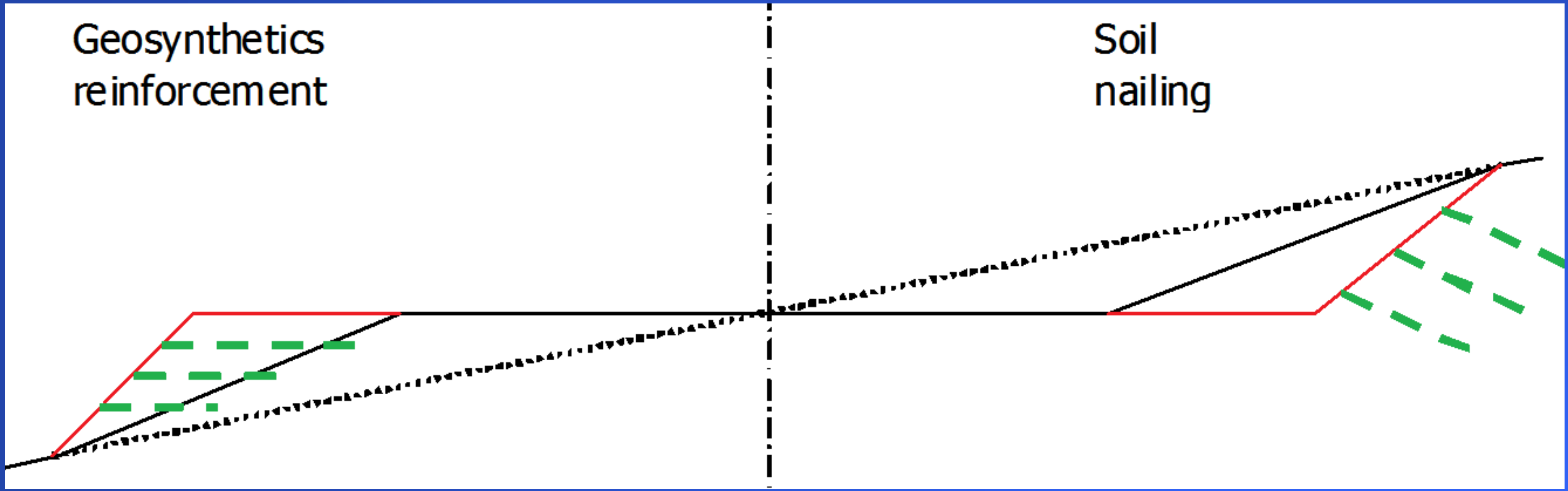




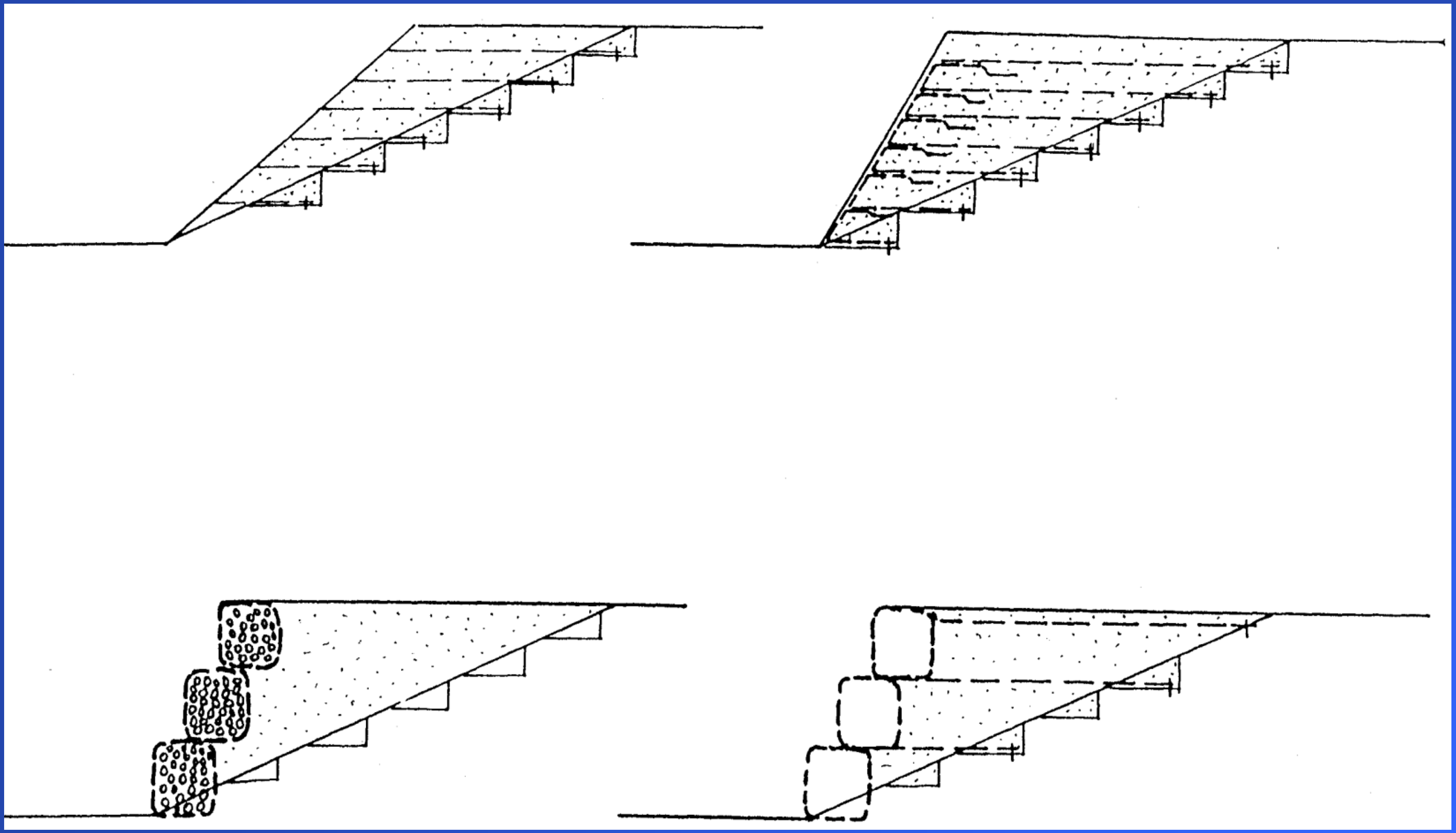
Reinforcement (1) alternatives of the contact between fill (3) and basement / subsoil (2)



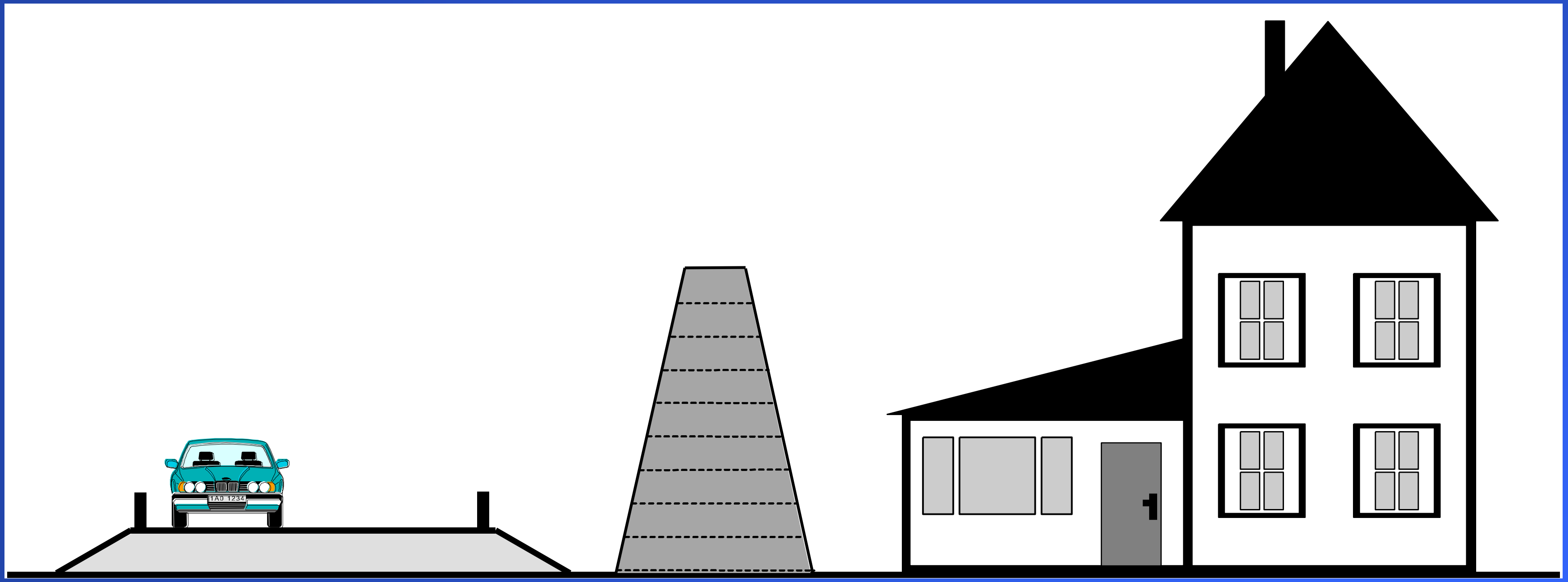
Road widening



Embankment widening



Noise protection bund



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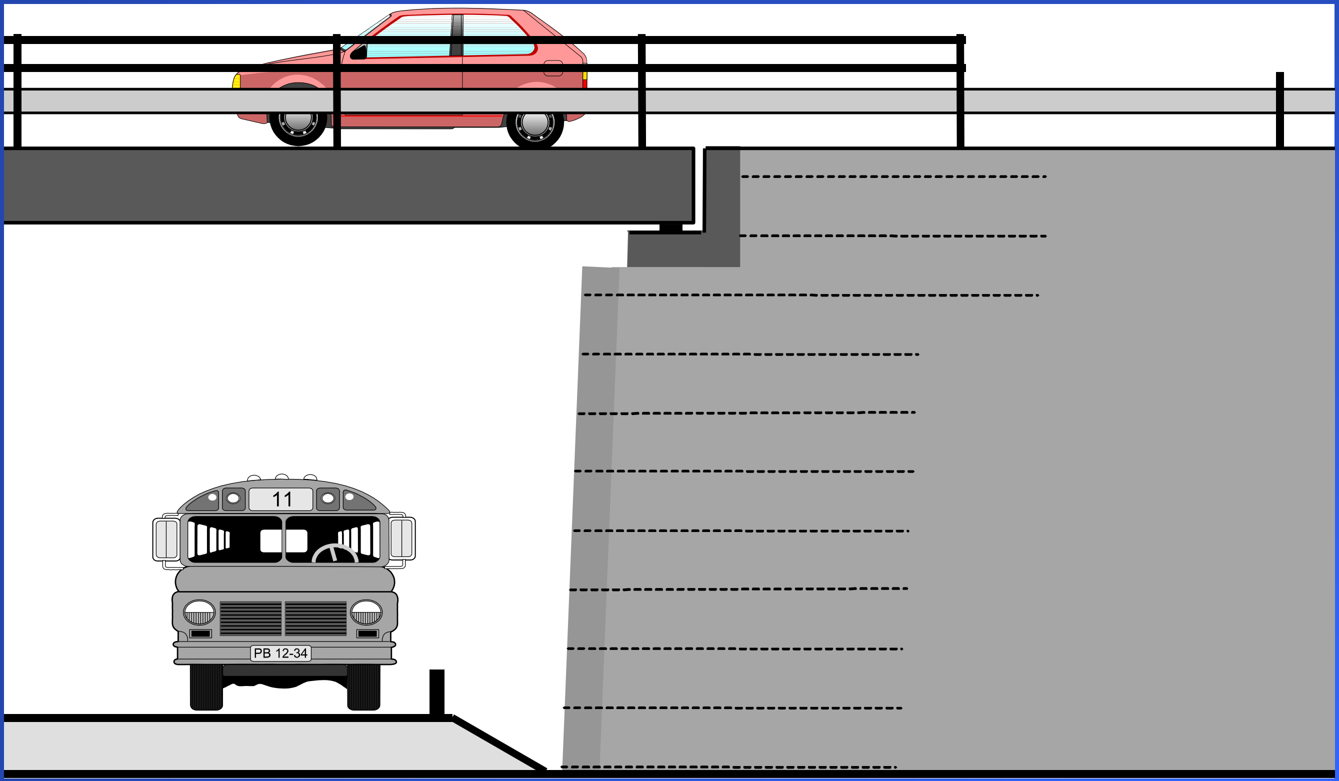
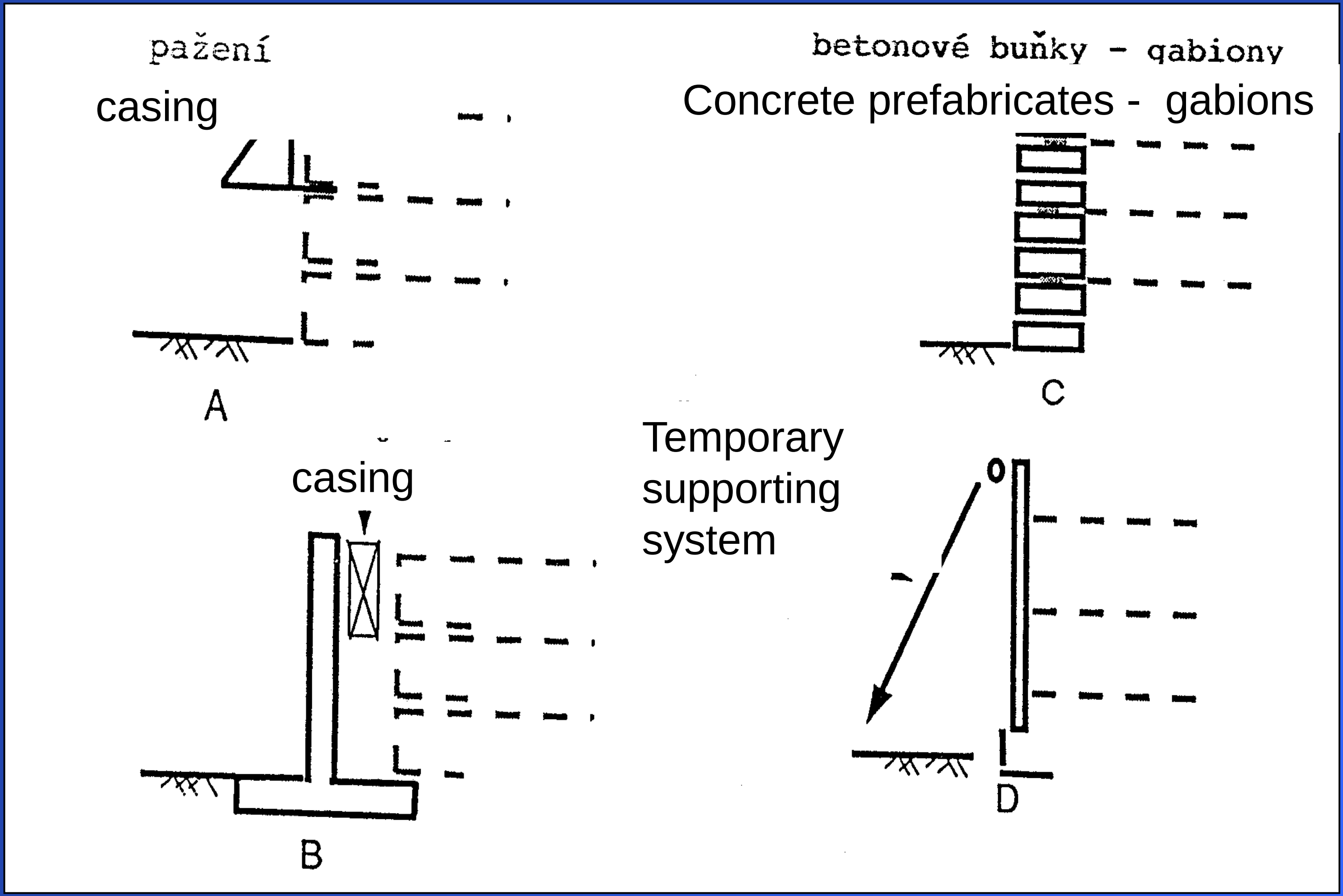
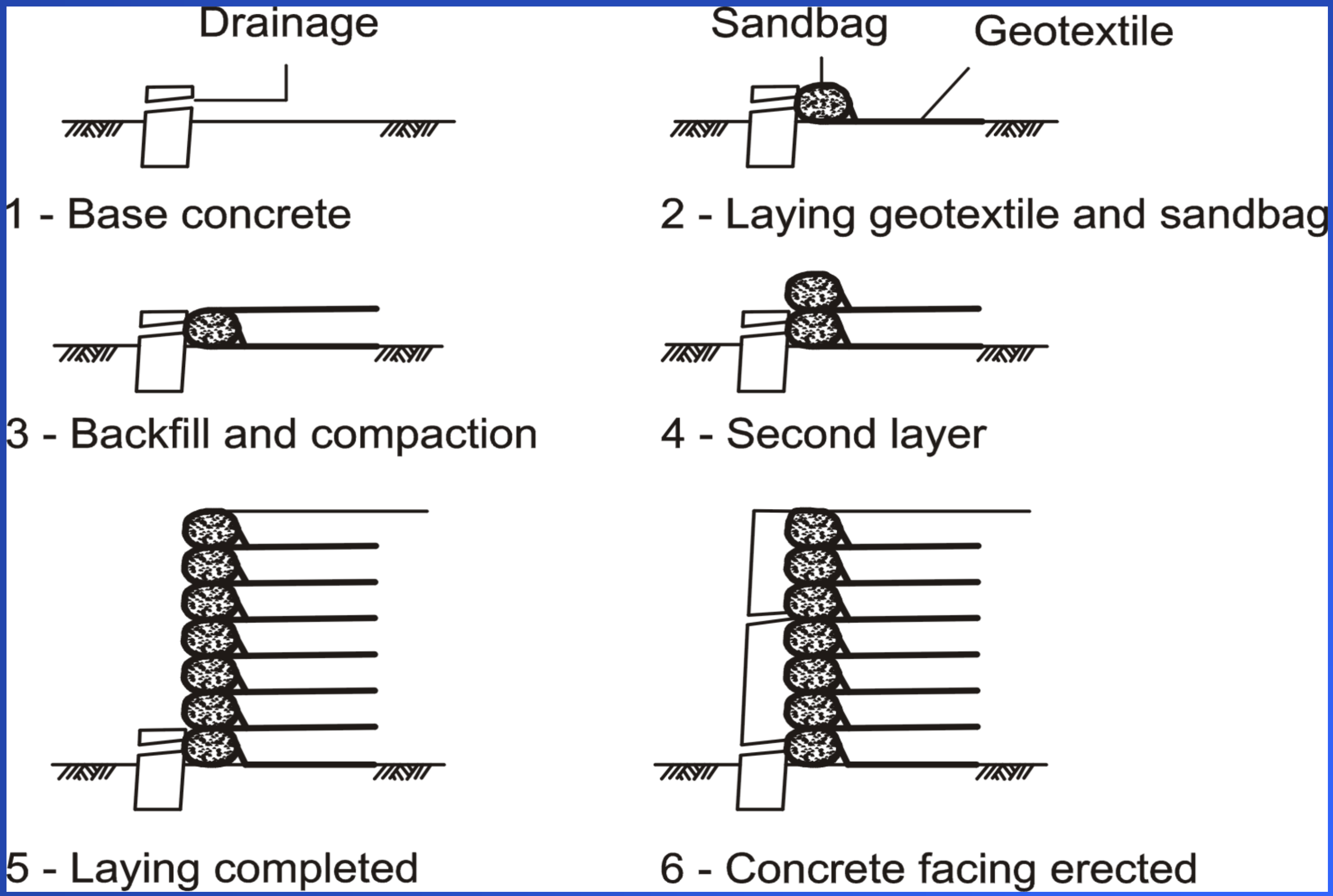
Bridge abutment



Retaining walls – construction systems



Construction steps of the reinforced wall used in Japan



Fundamental demands on reinforcing elements

- **Tensile strength and maximum elongation at failure**
  (strength for acceptable elongation)
- **Shear strength of the contact**
- **Creep properties of reinforcing materials**

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chemical
mechanical > **resistivity**

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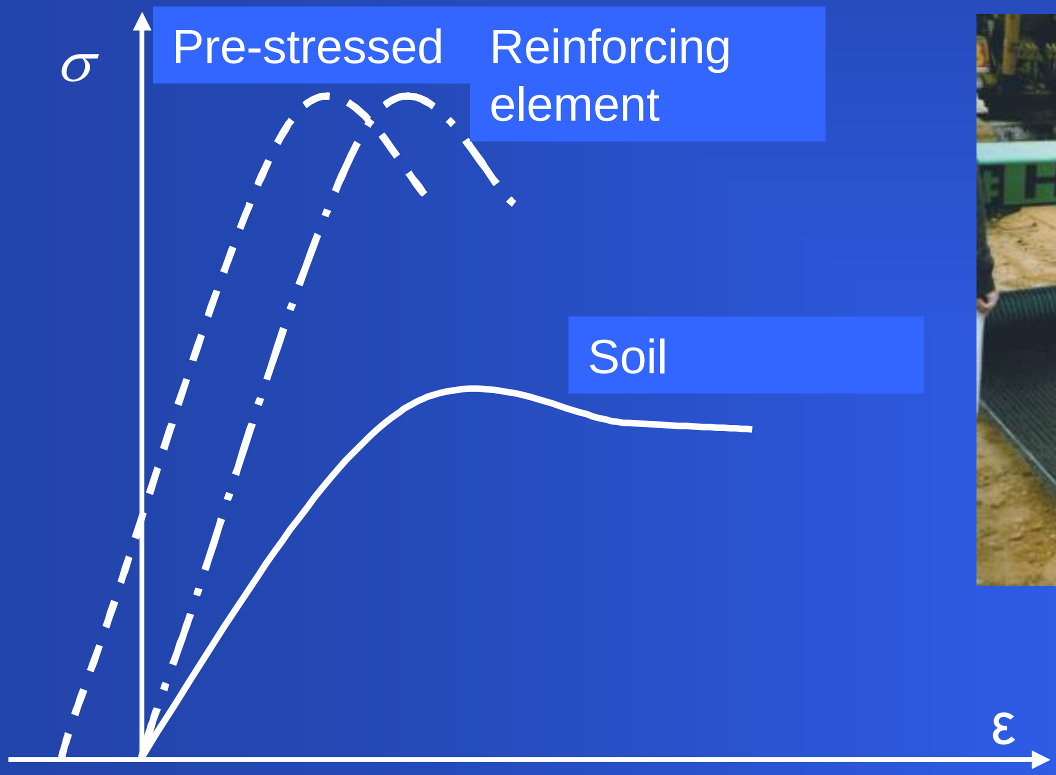
- **Polyester**
- **Polyvinylalcohol**
- **Aramid**
    - ❑ **High strength for small elongation**
    - ❑ **Excellent creep properties**

Product - geotextile < **woven** / **knitted**

- geogrids < **woven** / **extruded**

- geocells

TENSILE STRENGTH AND ELONGATION



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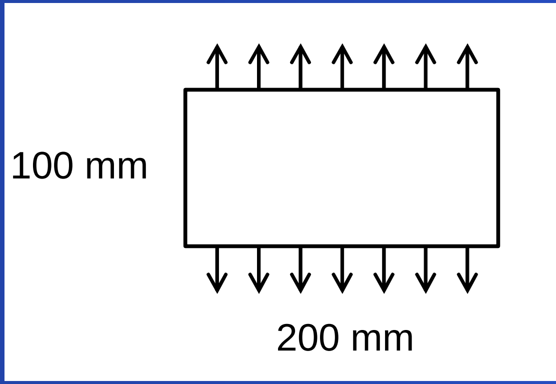
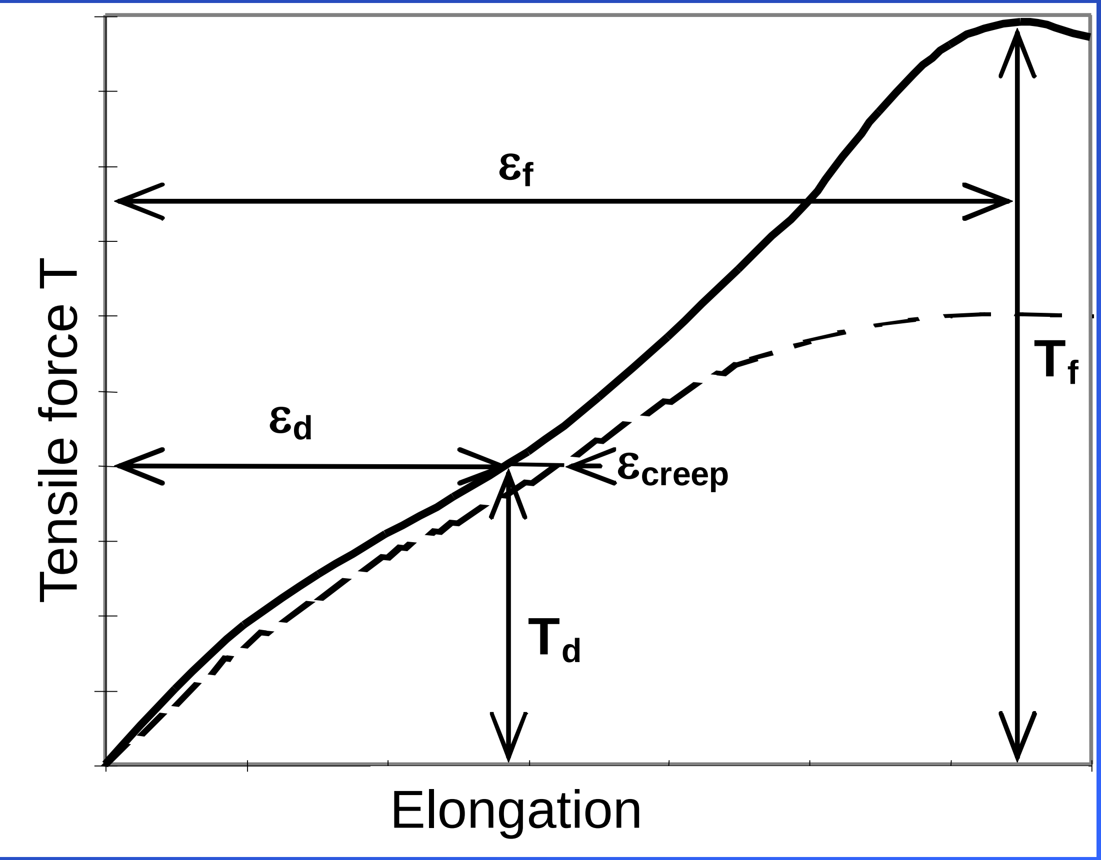
Stress – strain behaviour of geosynthetic materials





$T_f \rightarrow$ 1200 kN/m

$\varepsilon_f \rightarrow$ 6 - 12 %

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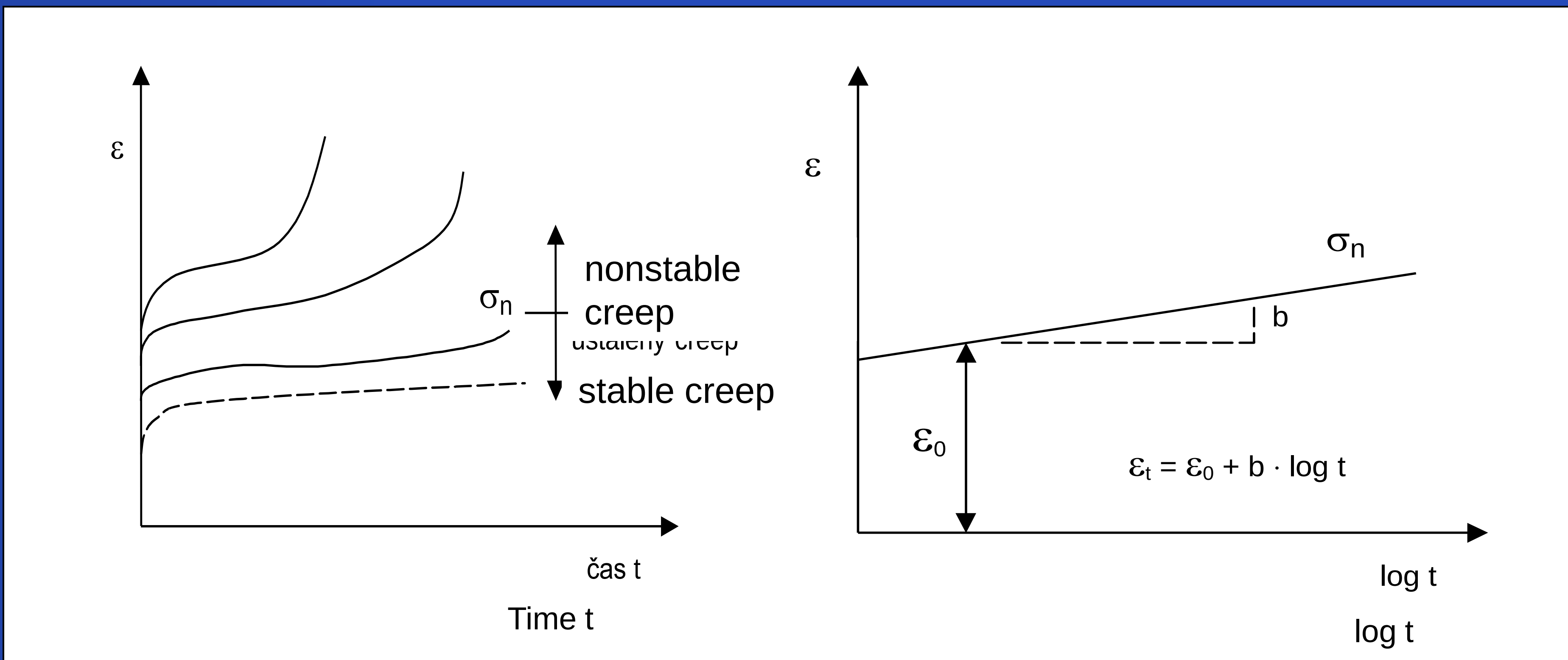
Creep



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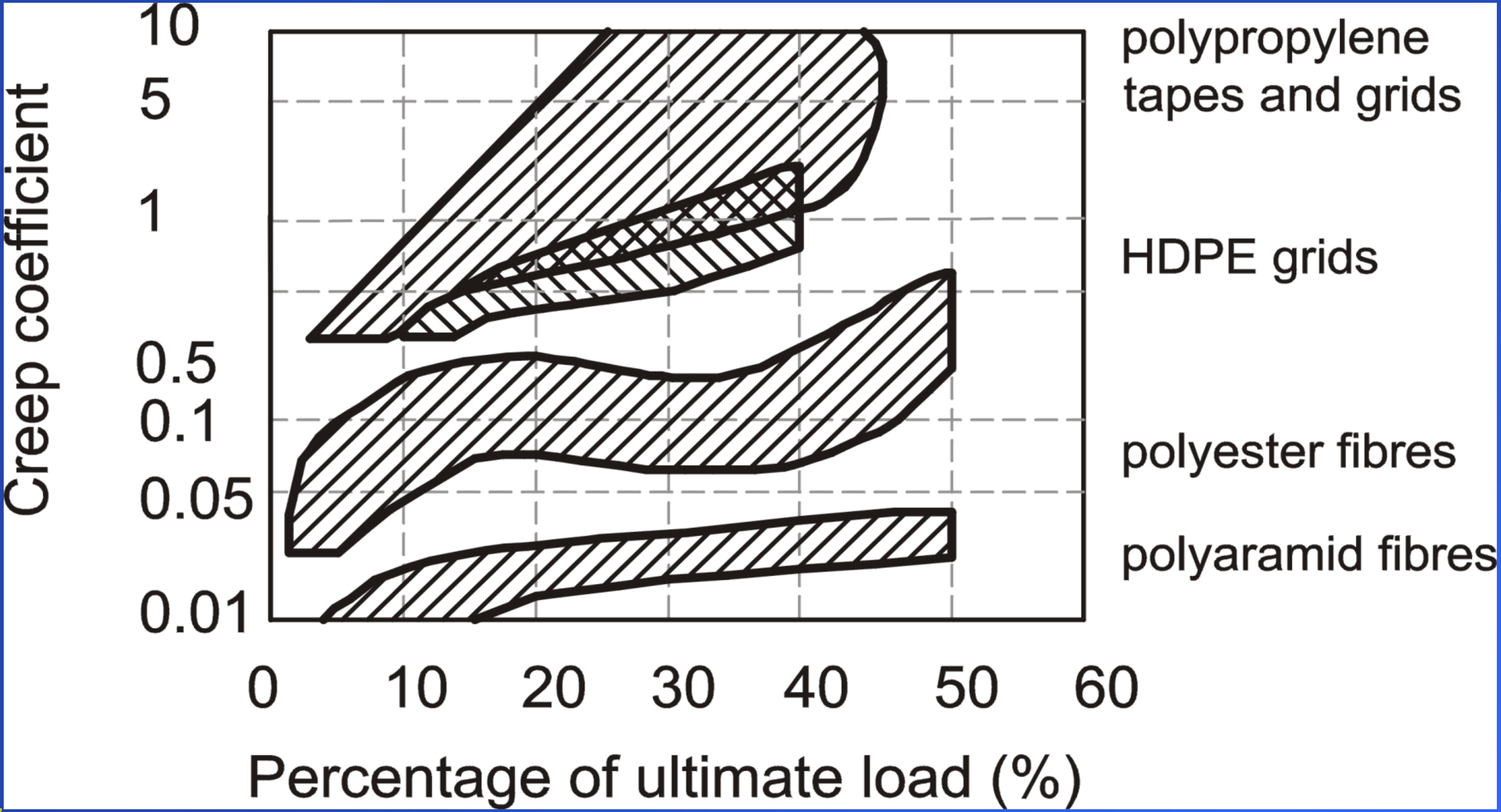
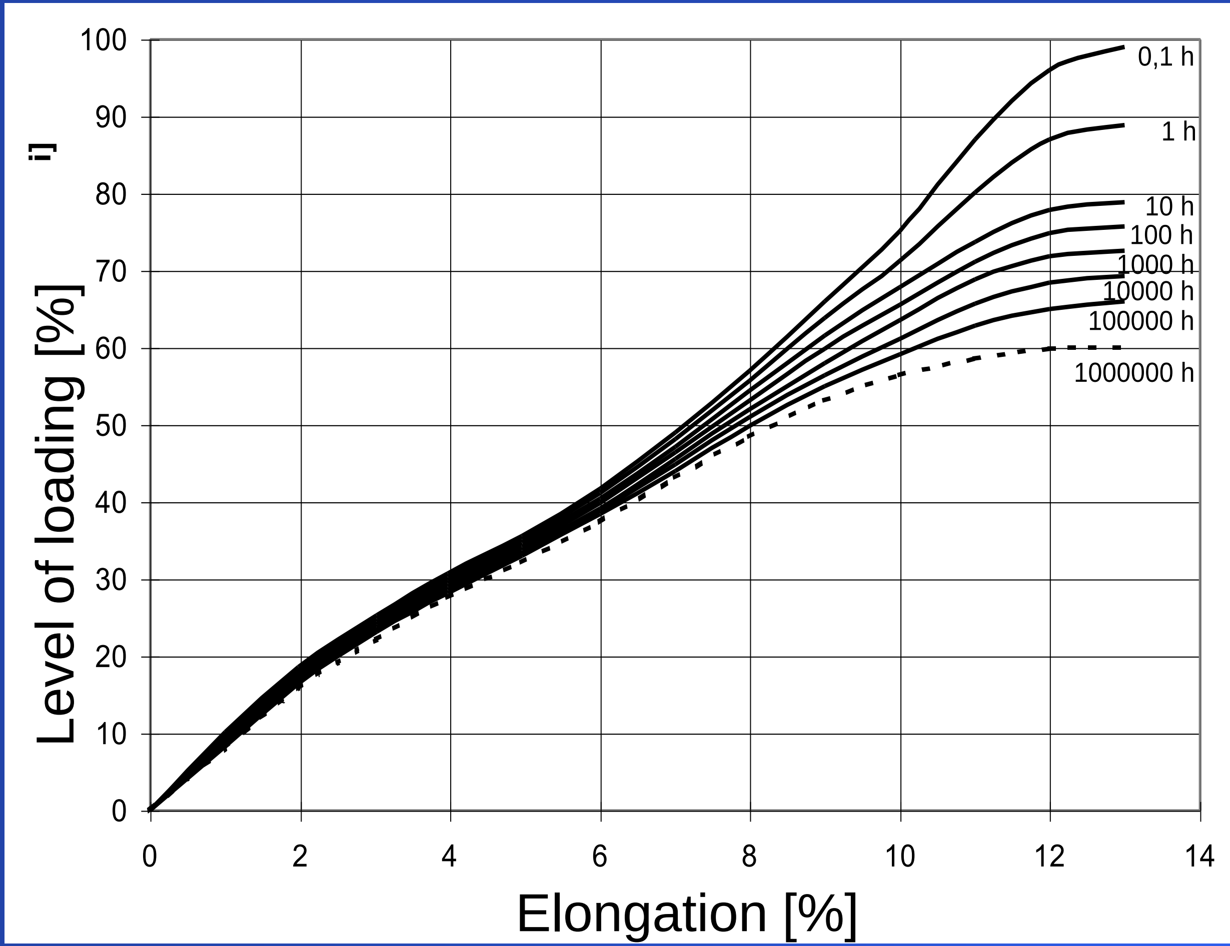
Creep coefficient b as a function of load level for basic polymers



Creep



a) polyester (geogrid Fortrac®)

General condition for realized structures:

<1% - retaining walls

<0,5% - bridge abutments

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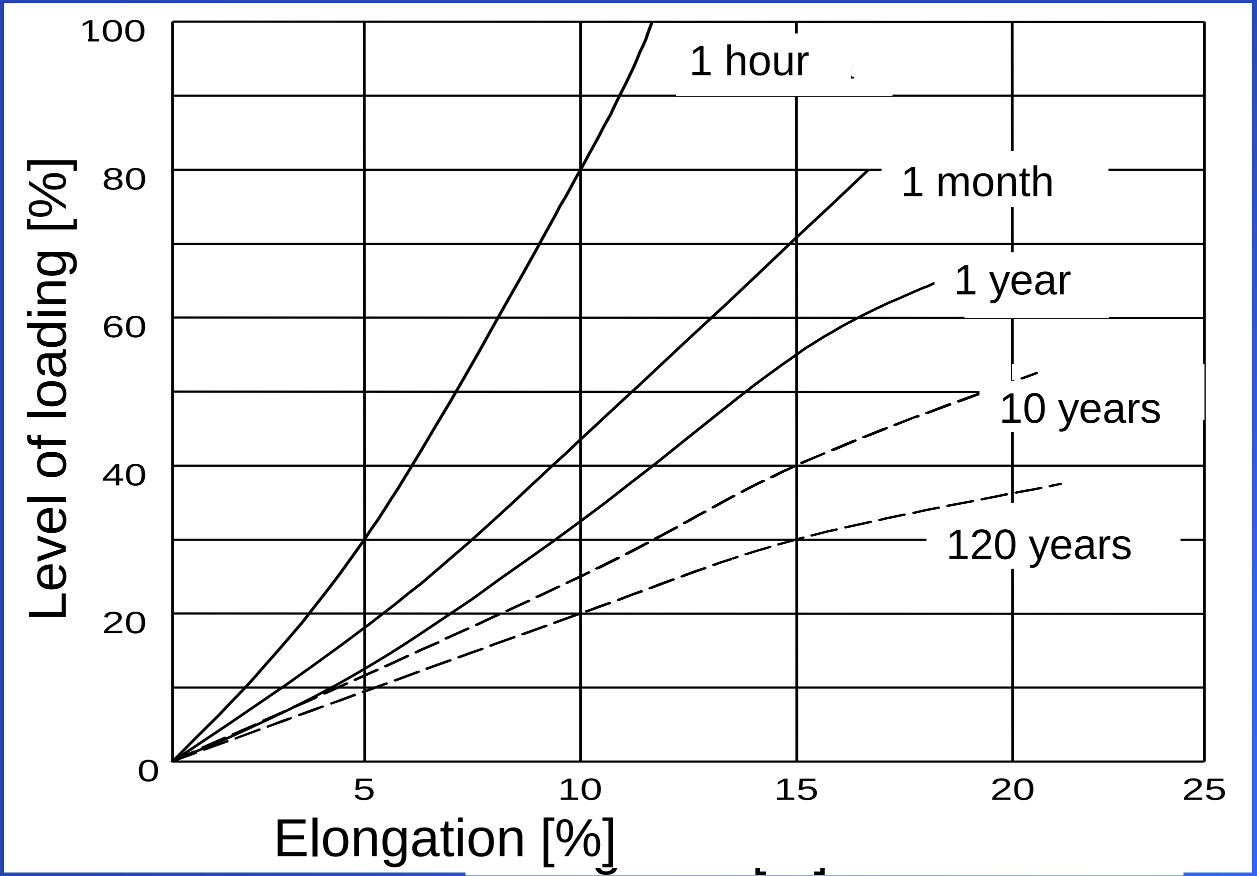
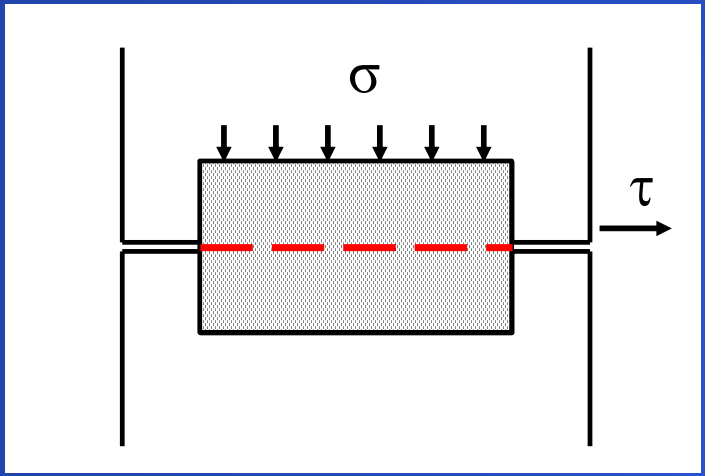
Creep



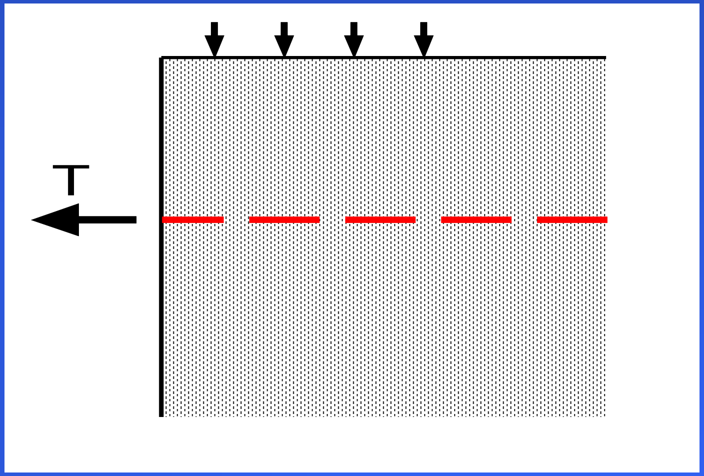
b) Polypropylene

Shear strength along contact

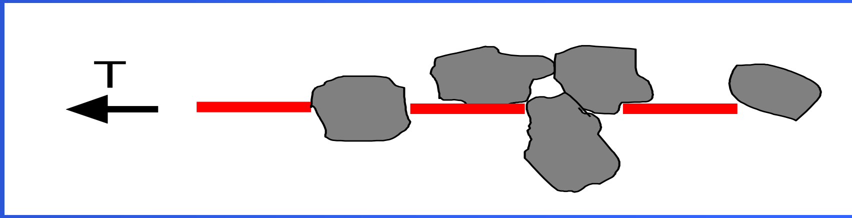
Sliding test



Pull out test



Geogrids



$$tg\varphi_{gs} \leq tg\varphi$$

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REINFORCED EARTH STRUCTURES DESIGN

Limit state

- Loss of overall stability or bearing capacity
- Deformation including creep which can cause
  - lost of serviceability of structure
  - structural damage of surrounding structures

- Surface erosion
- Internal erosion
- Uplift

EC 7 – 3 G Categories

LIMIT STATE DESIGN APPROACH:

- **Numerical modelling** – different numerical methods
- **Laboratory modelling**
  - centrifuge (Porhaba, Goodings 1996)
  - stereofotogrammetry (Vaníček 1978, 1980)
- **Modelling 1:1** – real structures
  – approval
  – future utilization - analogy

NUMERICAL MODELLING

- Classical methods
  - Stability (LEM) - ULS
  - Deformation (1D, 3D) - SLS
- Stress-strain numerical methods – FEM (1×SLS+1×ULS)
  - deformation
  - state of stresses – local failures

LIMIT STATE OF DEFORMATION

- **From experience / previous projects**
- **Estimation – according to the accepted elongation of reinforcing elements**
- **Laboratory simulation models**
- **FEM**

Classical methods $s_{calc.} \geq s_{real}$
(without reinforcement)

LIMIT STATE OF STABILITY

Limit equilibrium methods

$$\gamma_{sit} \cdot \gamma_{n} \cdot \psi_{c} \cdot \Sigma\gamma_{fai} \cdot S_{act,in} \leq \gamma_{stp} \cdot \Sigma\gamma_{fpj} \cdot S_{pas,jn}$$

simplified case:

$$\Sigma S_{pas,jn} / \Sigma S_{act,in} \geq \gamma_{n} / \gamma_{stp}$$

$$\Sigma S_{pas,jn} / \Sigma S_{act,in} \geq 1{,}22 - 1{,}33$$

γ_n - structure significance 1,1 -1,2 (risk factor)

γ_{stp} - stability calculation 0,9 (model factor)

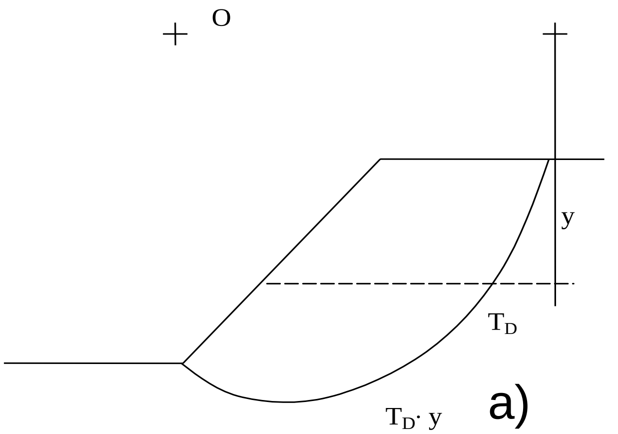
DESIGN STRENGTH

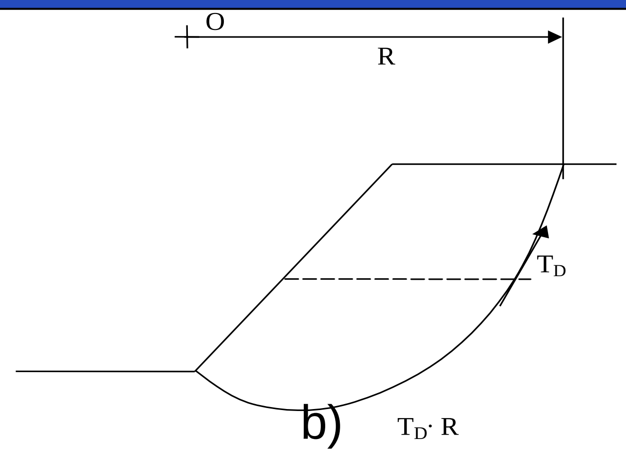
- **Soils φ_d , c_d**
- **Reinforcing element** $T_d = \frac{T_f}{F_{tc} \cdot F_{comp} \cdot F_{env} \cdot F_{mat} \cdot F_{ost}}$ **, where**

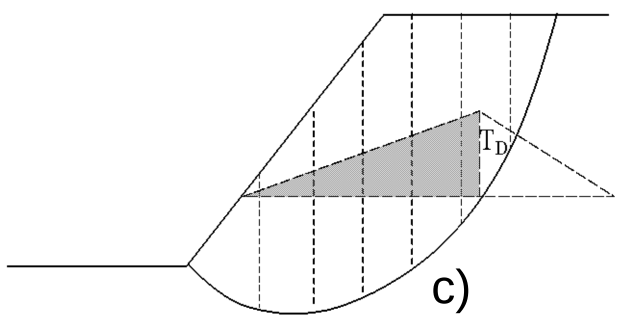
Partial factors of safety for different standards:

Standard	F_{comp}	F_{env}	F_{tc}		F_{mat}	F_{ost}
			PET	PP PE		
FHWA (USA)	1,25 - 3	1,1-2	2,5	5	1,5	-
CFGG (F)	1,1 - 1,5	1,1	2,5	4,5	1,2	-
Gourc (F) (NFP – 38064)	1,1 - 1,5	1,1	2,25	4,5	-	-
DGGT (D)	1,1 - 1,5	1,1	2,5	4	1,75	-
Polyfelt	1,3 - 1,5	1,1	2	4	1,2	-
TP 97 (1997) + ČD (CZ)	1,1 - 1,5	1,1	2,5	4,5	-	1,22 - 1,33

Reinforcement implementation into limit equilibrium methods







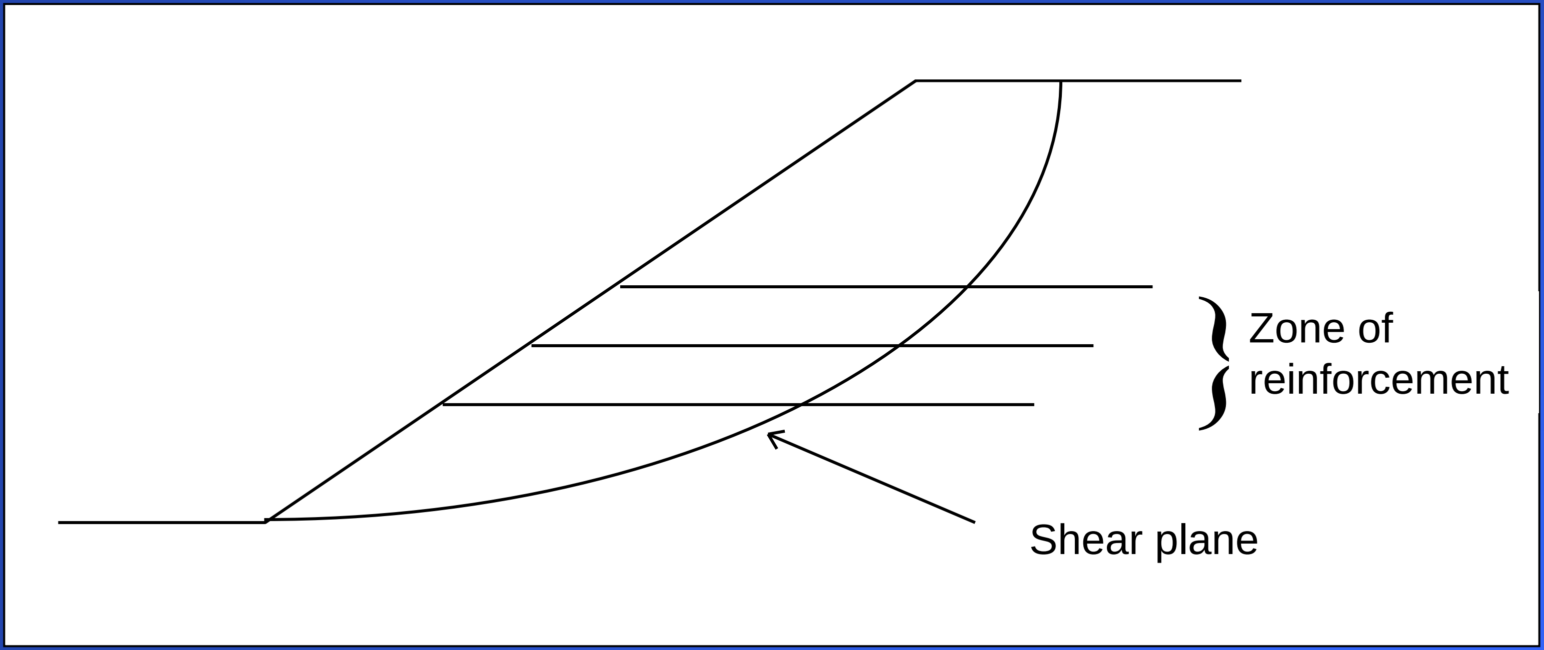
Assumptions for reinforcement implementation into stability calculation

a) Moment from T_d on lever-arm y (variable)

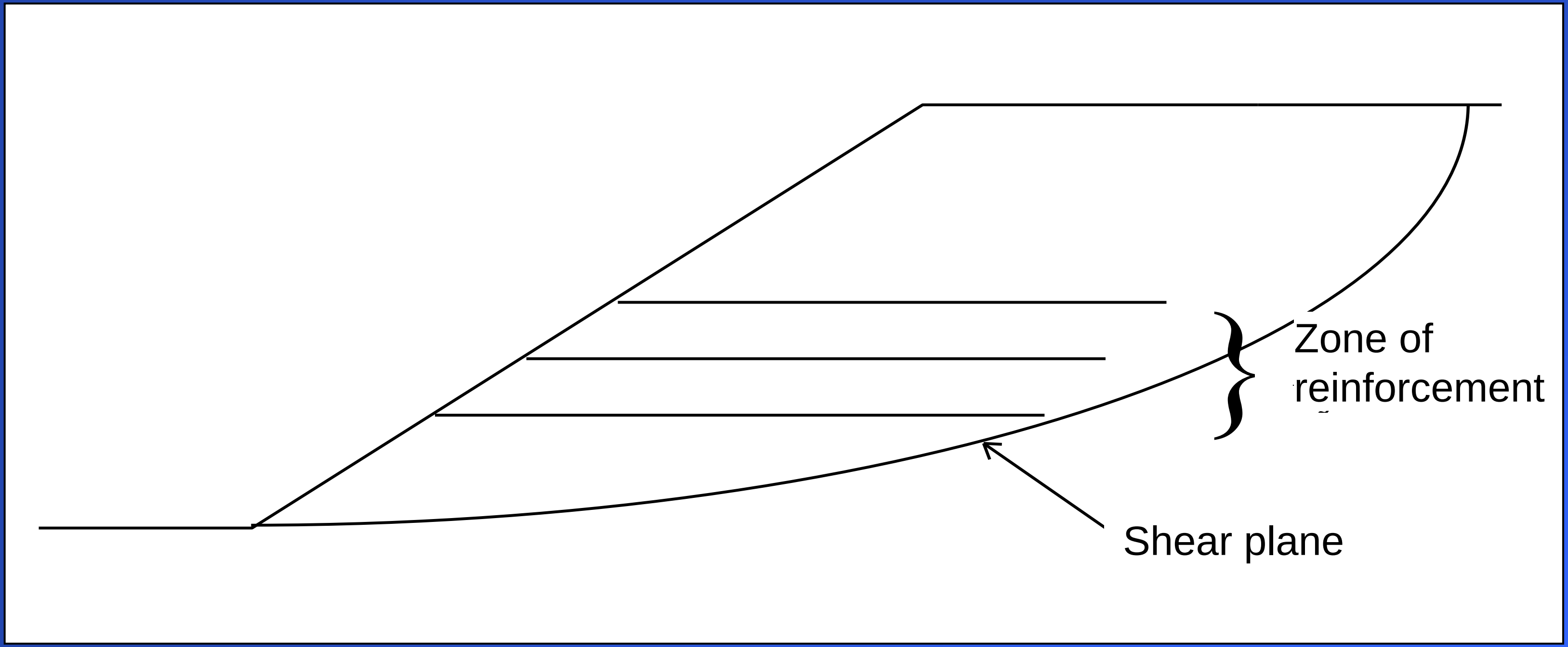
b) Moment from T_d on radius R (constant)

c) Additional inter-slice force (variable effect)

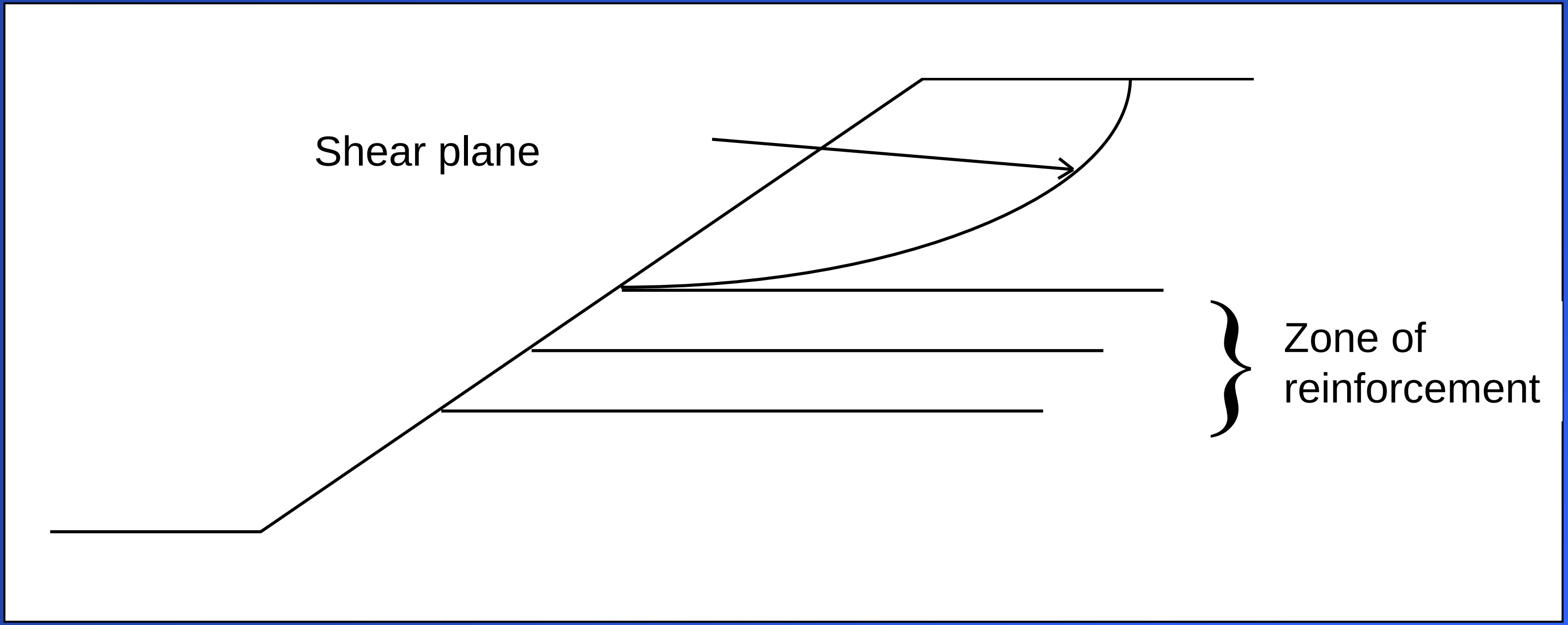
Shear plane passing through reinforcing elements - Internal stability



Shear plane passing outside of zone of reinforcement
- External / overall stability

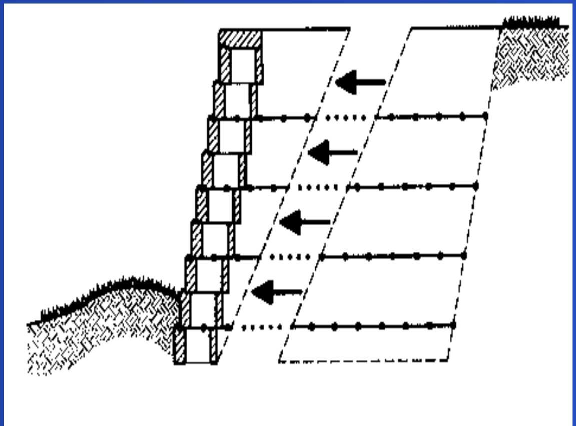


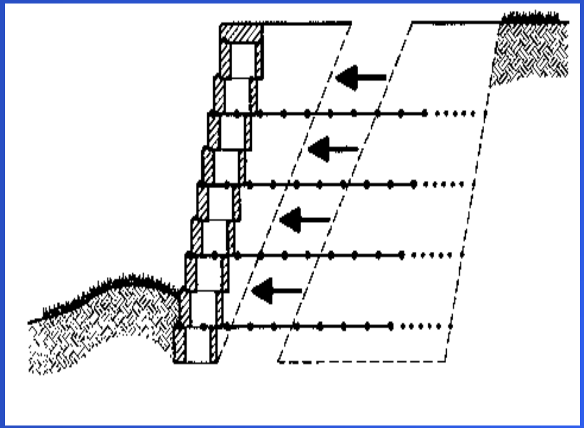
Shear plane passing outside of zone of reinforcement - External / local stability

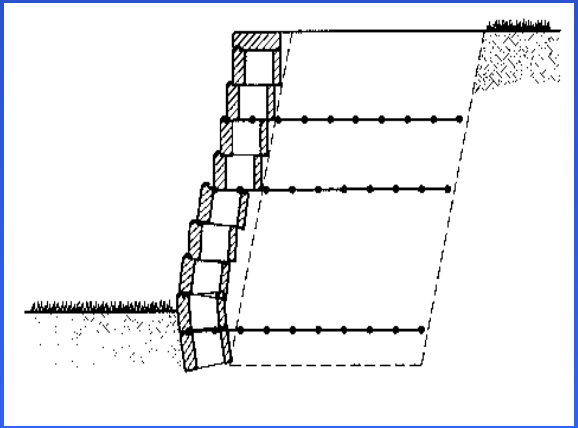


Critical cases for retaining wall

- Internal stability







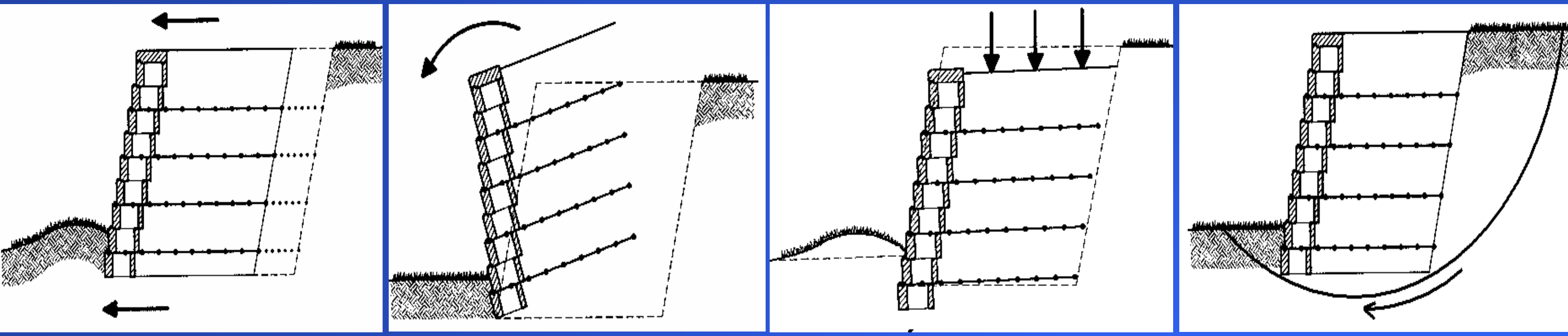
Failure of reinforcing element (overstressing)

Pull out

Buckling of facing elements

Critical cases for retaining wall

- External stability



Sliding | **Overturning** | **Loss of bearing capacity** | **Overall stability**

Method of Janbu – software SVARG / GEO4

- Limit state equilibrium method
- General slip surface
- Automatic determination of design parameters for soil and reinforcing elements
- Automatic search for the most critical slip surface
- Automatic control of anchoring length

FEM

PROBLEMS:

- **Reinforcing element modeling thickness is very small – leading to enormous number of elements**
- **Modeling of interaction of the contact soil × reinforcing element**

Brown + Poulos (1978)
Rowe + Ho (1988)

- **Composite models**
- **Discrete models**

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FEM

Karpurapu + Bathurst (1994)

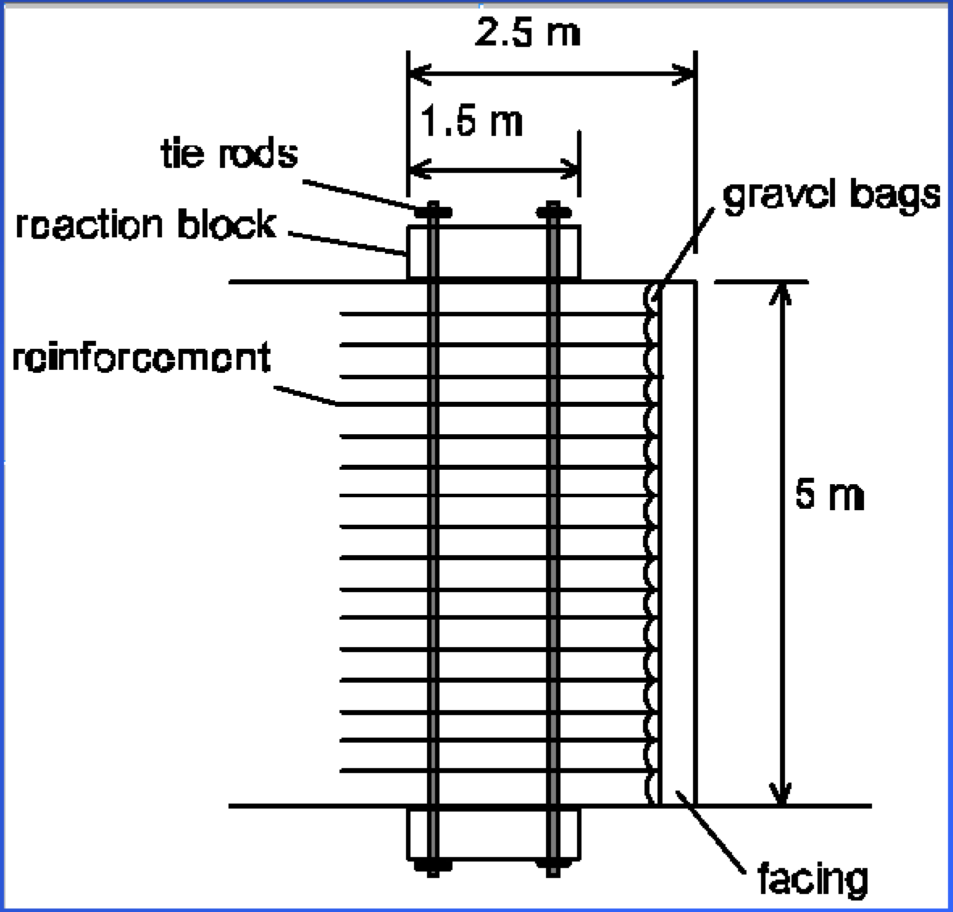
- **More general constitutive models for soil**
- **Special finite elements for contacts:**

  soil × reinforcing element

  soil × facing

Directions of new development

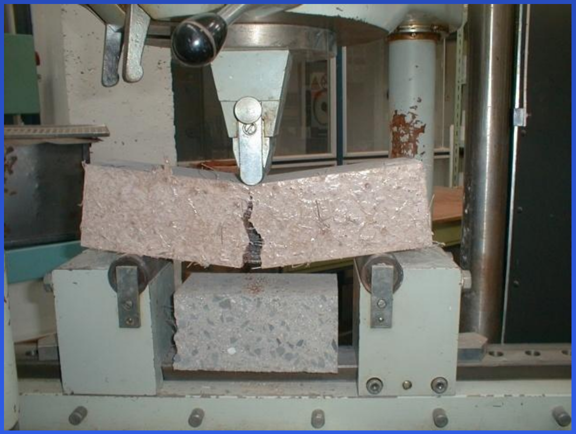
a) Prestressed reinforced earth structures

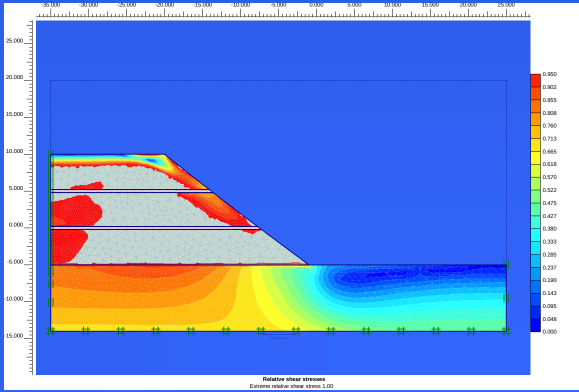


b) FEM – inclusion of creep for geosynthetic reinforcement

Directions of new development

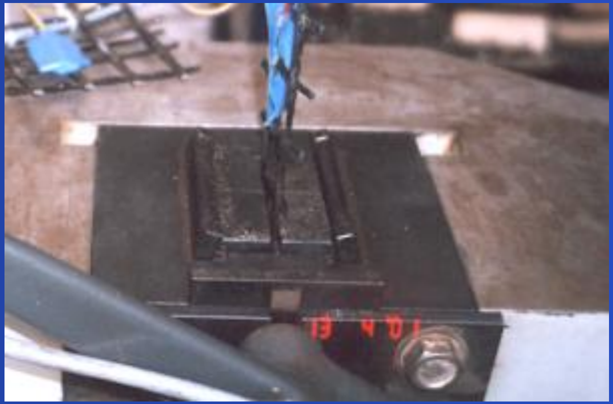
c) Randomly distributed short synthetic fibres





Directions of new development

d) Monitoring of strength × strain behaviour of geosynthetics in Earth structures



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Practical examples – RW reconstruction

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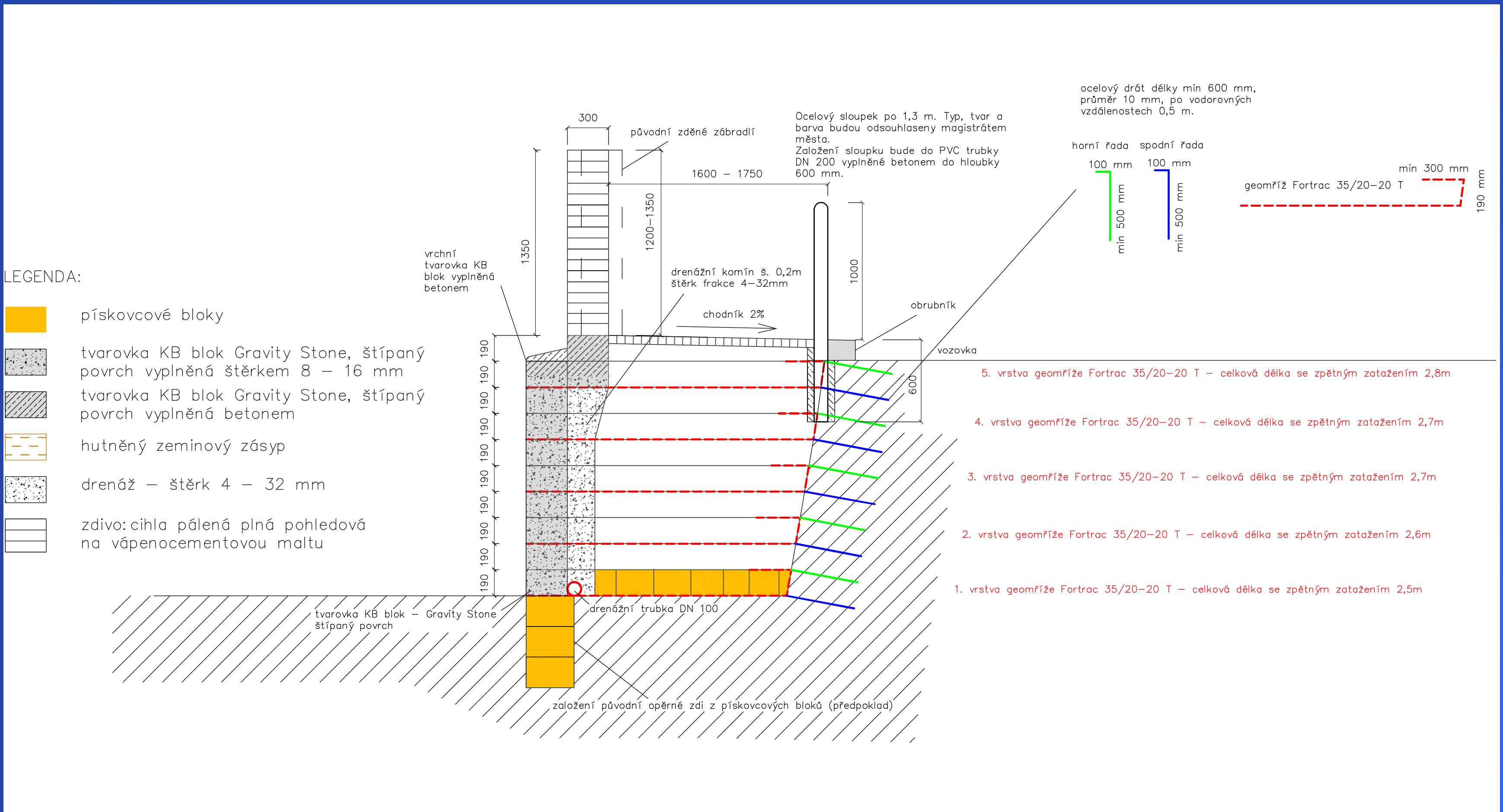

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Practical examples - Overturning

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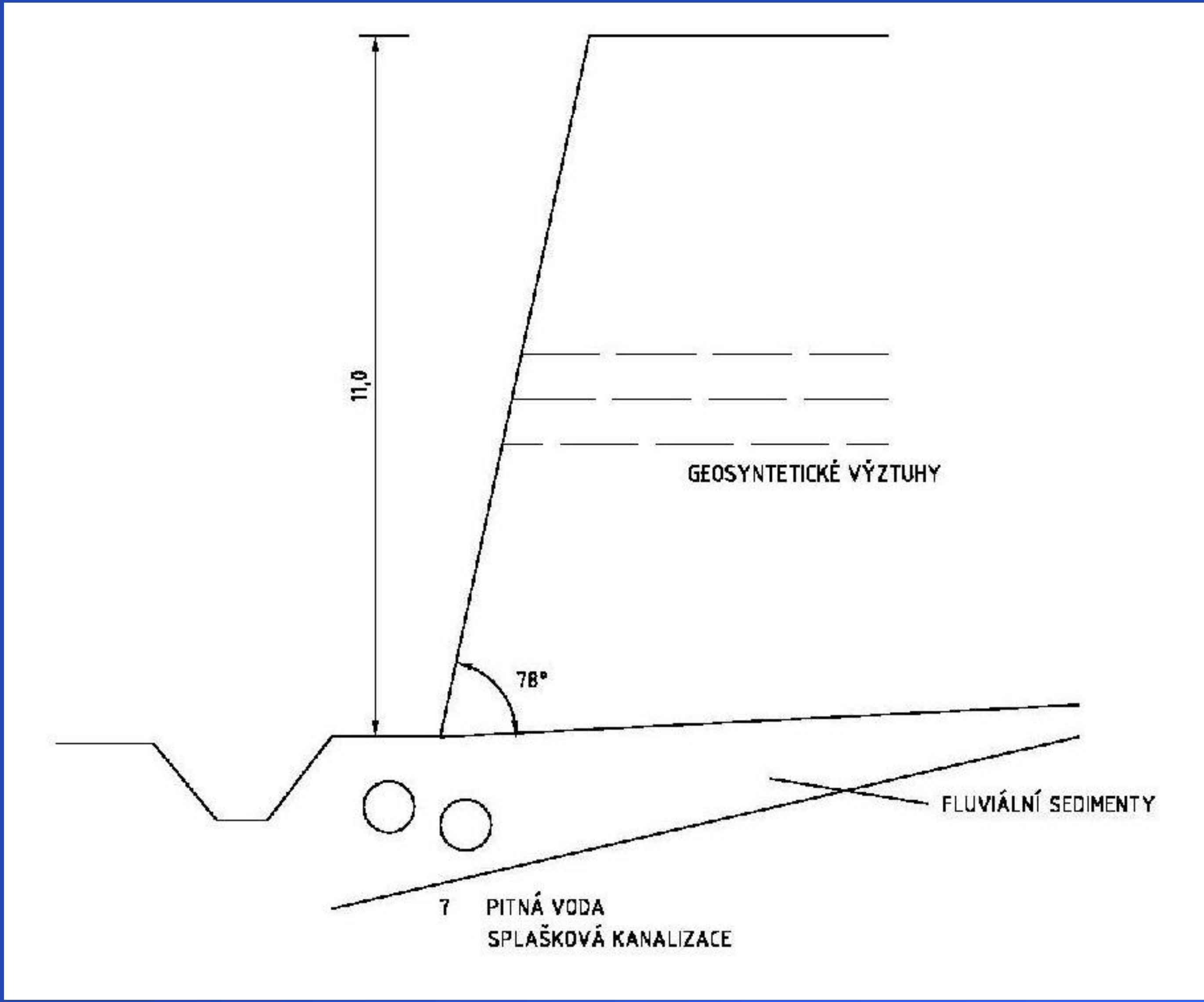
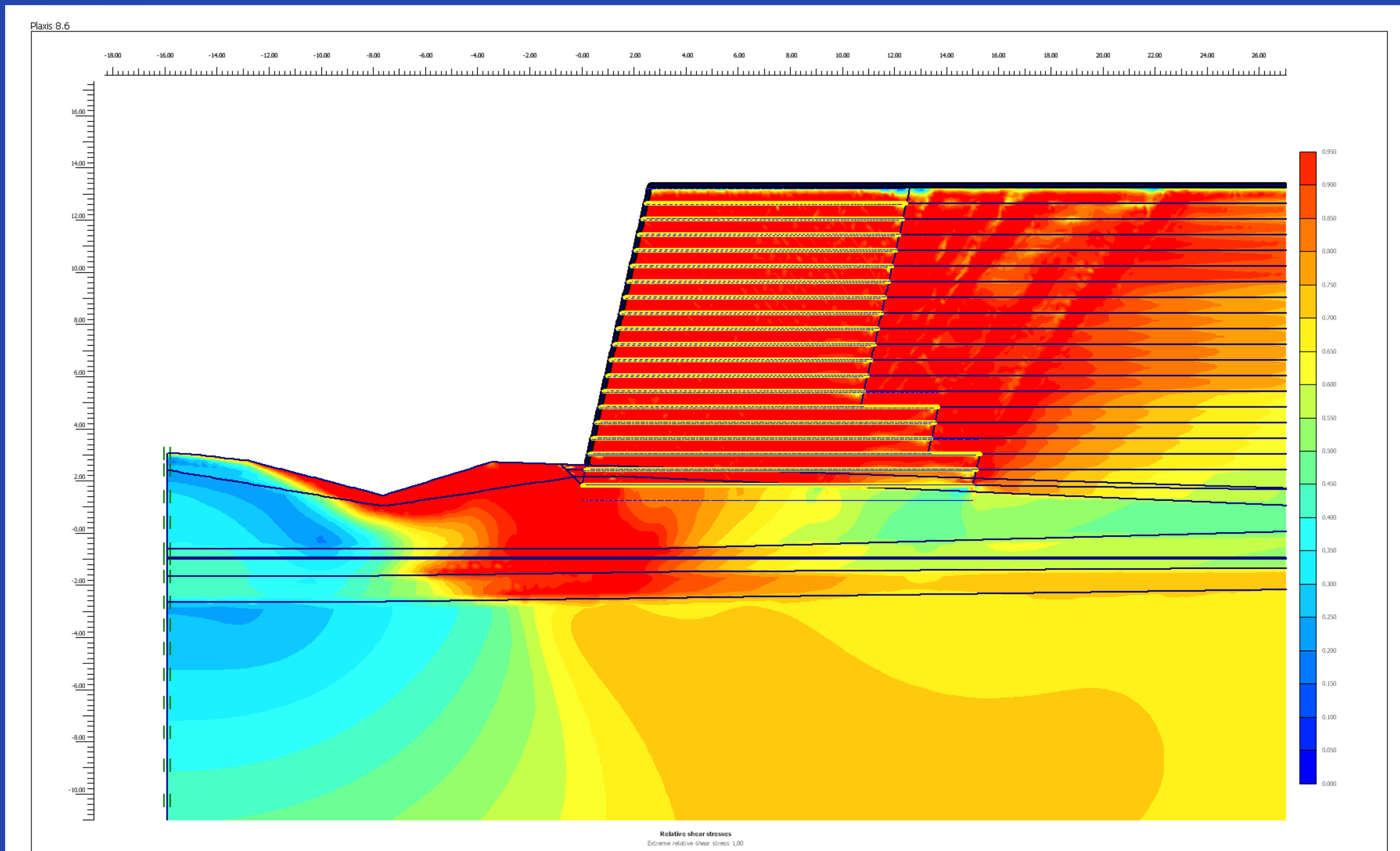
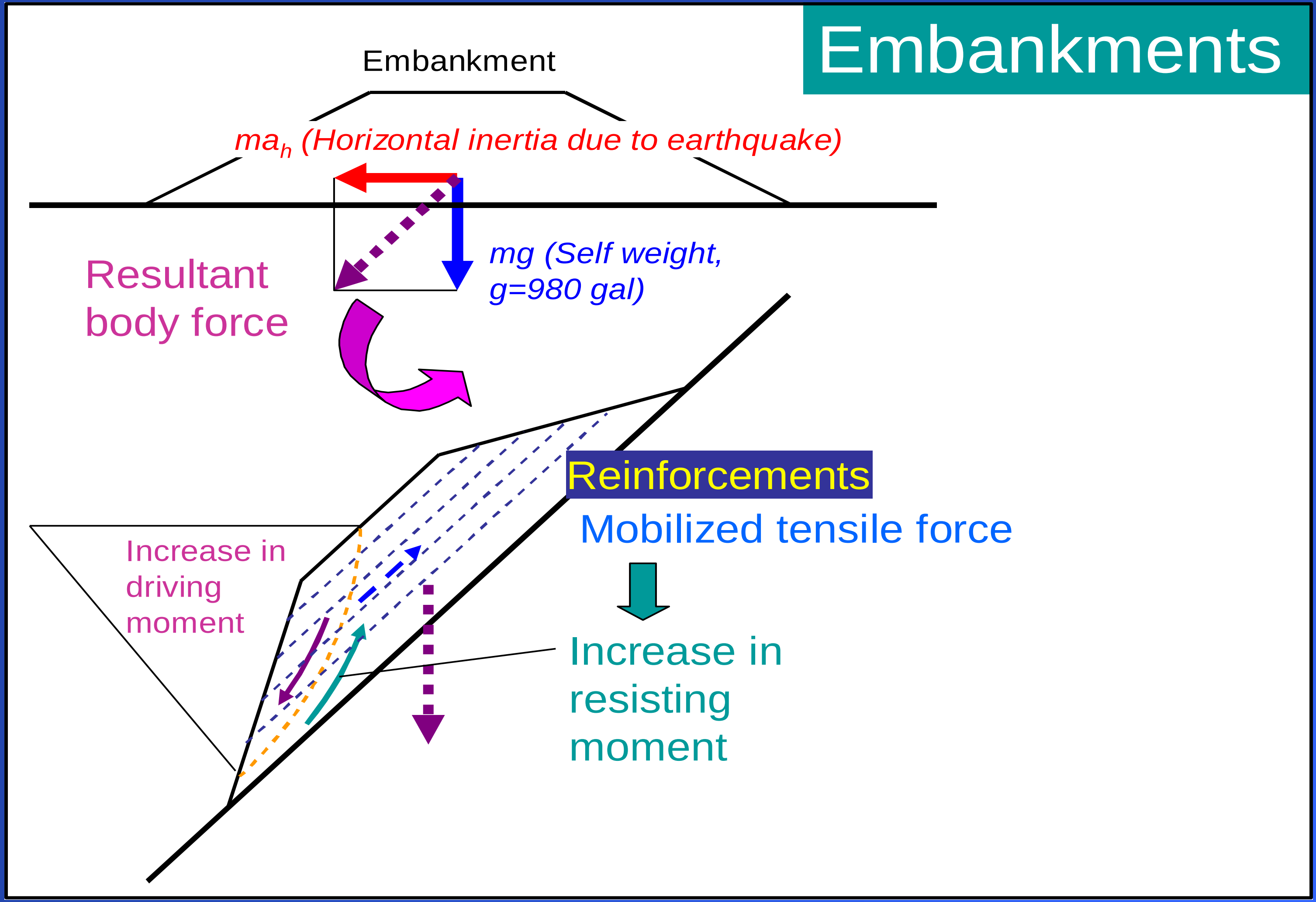


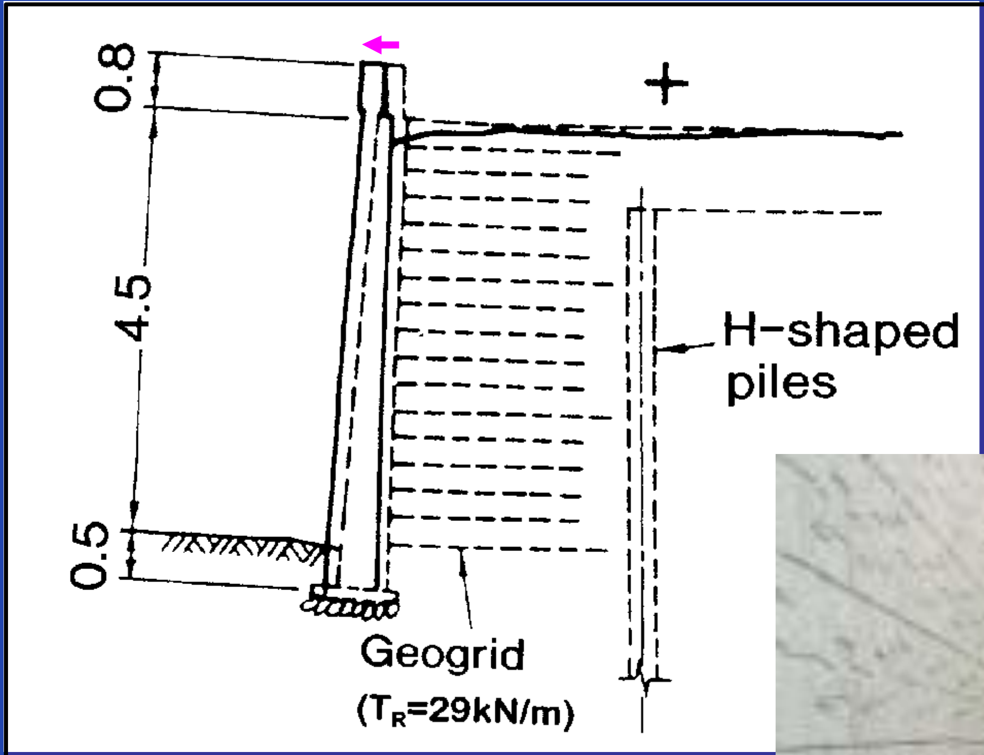
Practical examples - Overturning



Practical examples – earthquake Koseki 2010



Koseki - 2



1995 Hyogoken-Nanbu Earthquake

Residual disp. 10-20 cm
Could be re-used with minor repair
No deep foundation

GRS RW with FHR facing at Tanata site

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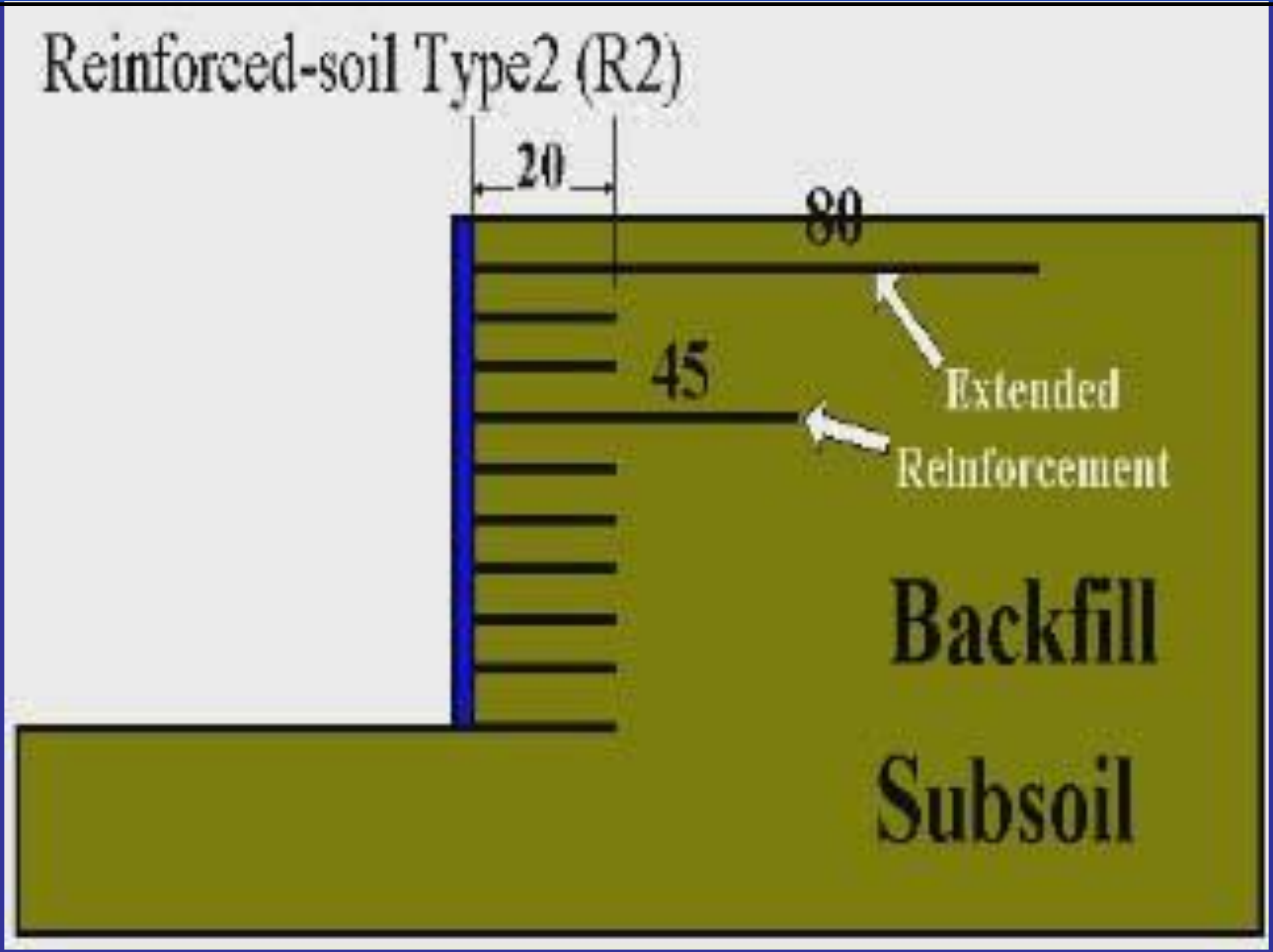
Koseki - 3

1999 Chi-Chi earthquake in Taiwan

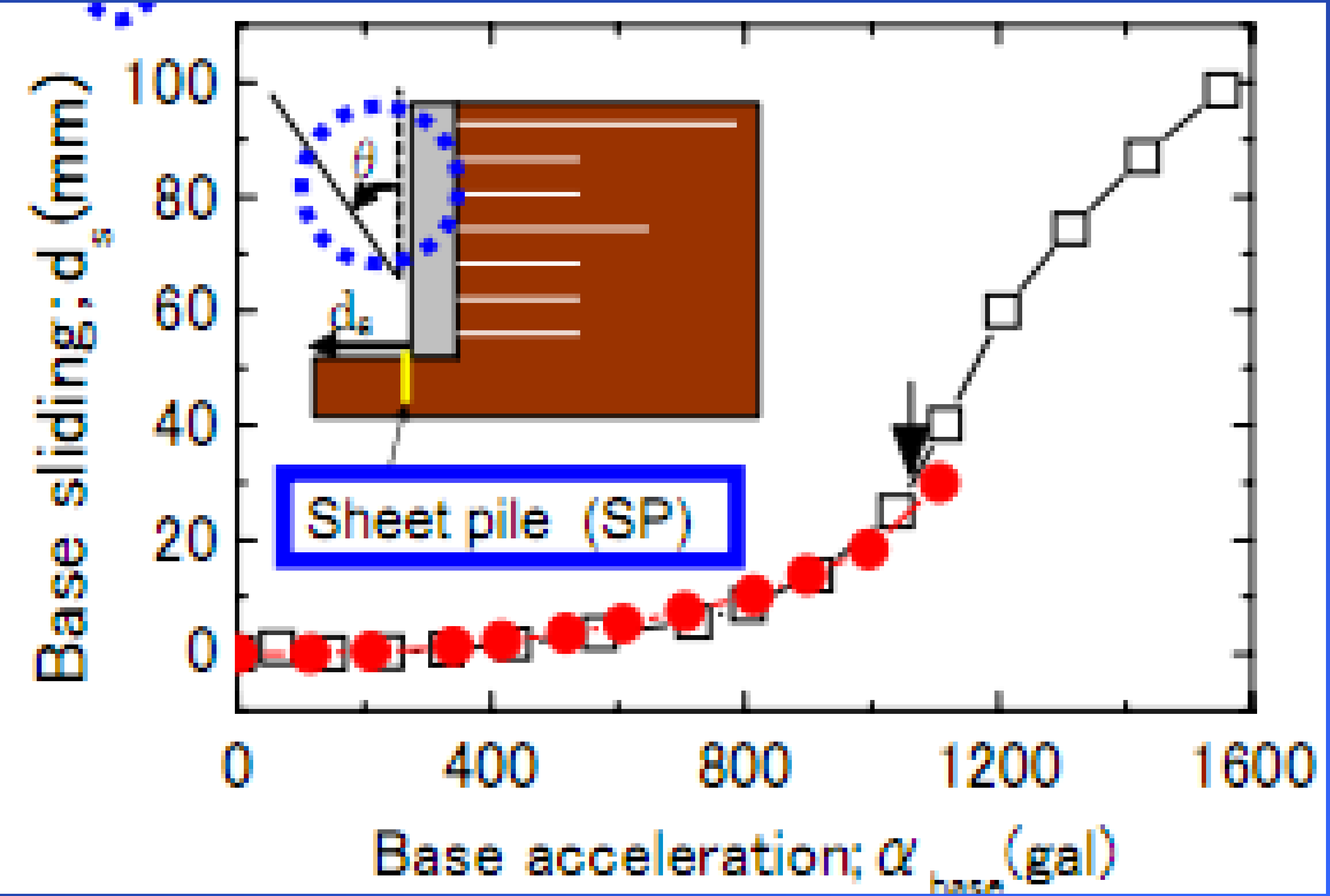
Damage to GRS RW <u>using precast-concrete blocks as facing</u> *(along District Road No. 129, Tai-Chung County)*

Koseki - 4



Response of GRS RW (R2) model in 1.1 g shaking

Koseki - 5


Base sliding; d_s (mm)
100
80
60
40
20
0
0
400
800
1200
1600
Base acceleration; α_{base} (gal)
Sheet pile (SP)
θ
d_s

CONCLUSION

Reinforced soil:

- **Structure containing two very different materials with sensitive interaction (composite materials)**
- **Application of limit state design**
- **Deformation**
- **Significance of monitoring**

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