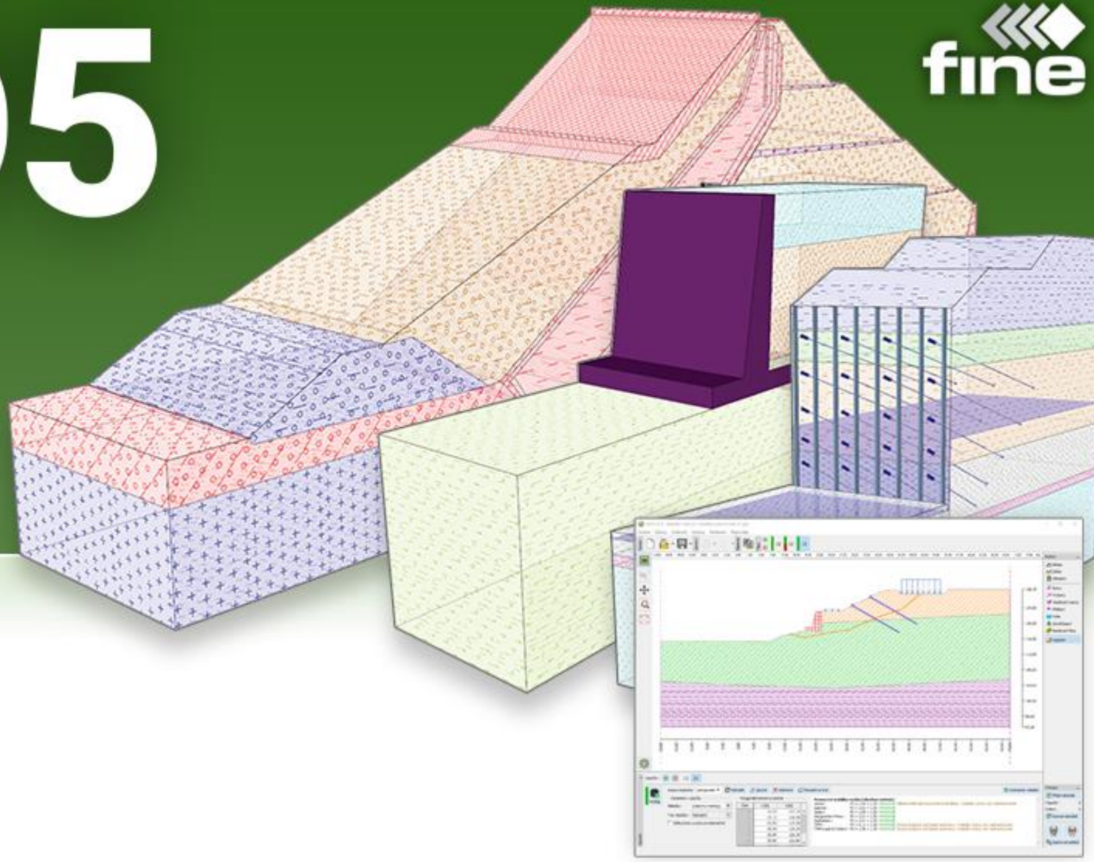
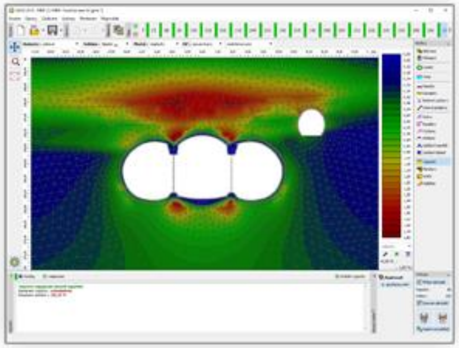
GEO5

Geotechnical Software





FEM
- elements, materials

Tomáš Janda

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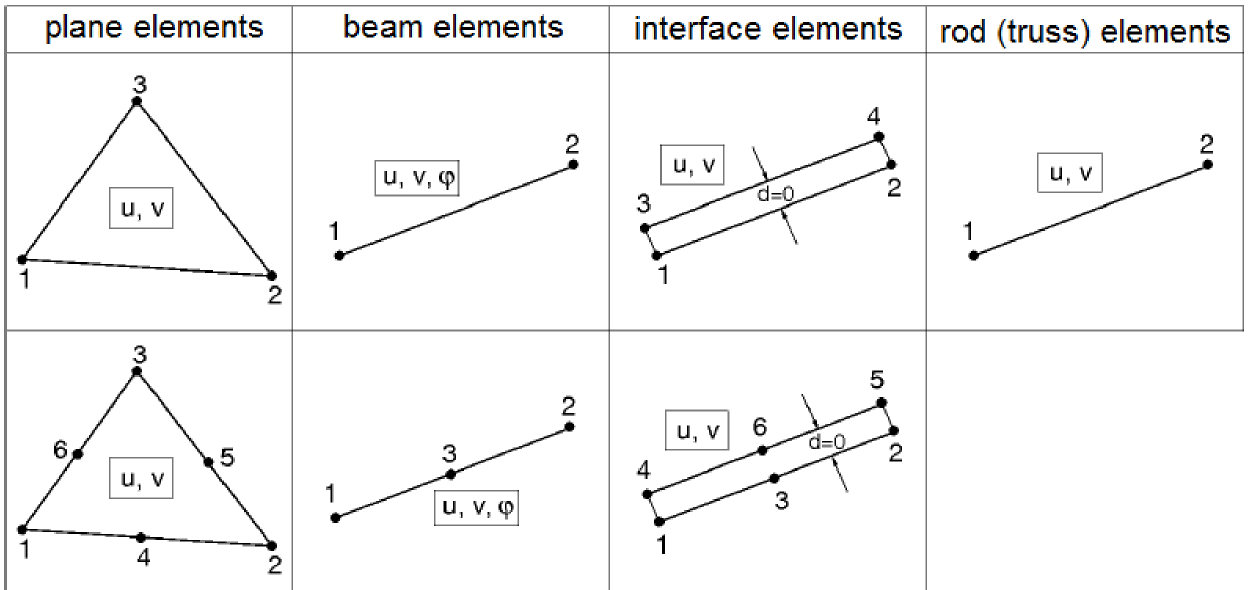
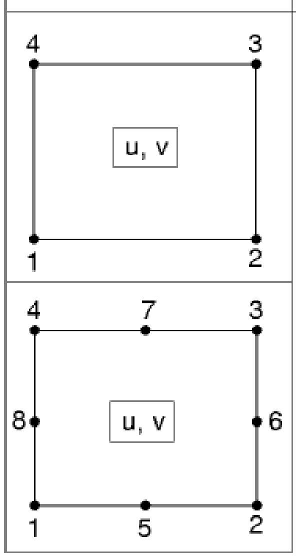
Outline

- Finite elements
- Structural elements
- Contacts
- Constitutive models (materials)
  - Elastic model, Modified elastic
  - Mohr-Coulomb, Drucker-Prager
  - Advanced models
- Driven tunnels
- Solution strategies, solver parameters

Finite elements

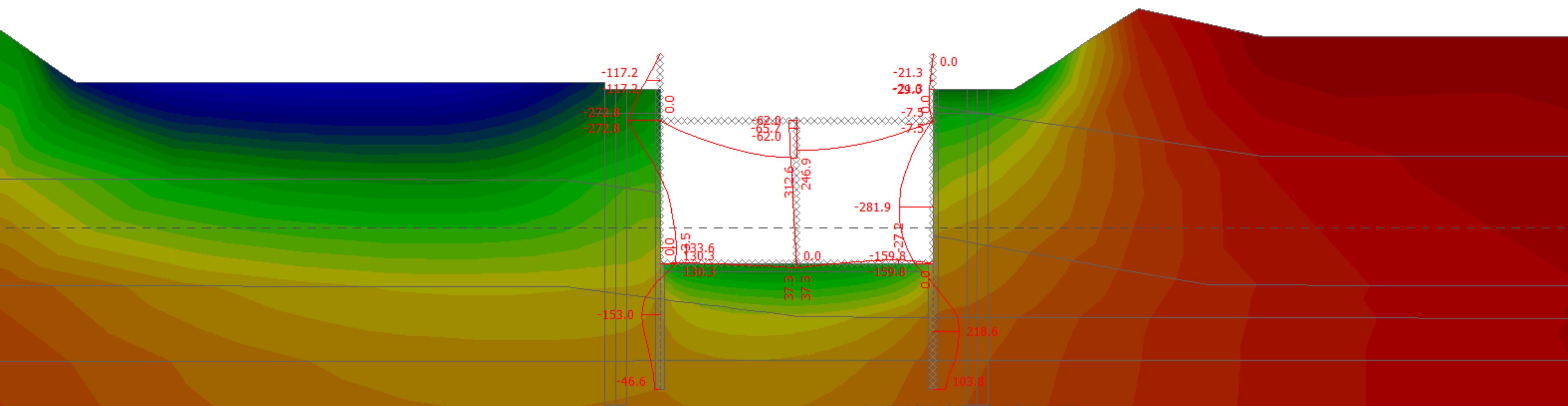




- Plane elements – two nodal degrees of freedom
- Beam elements – three nodal degrees of freedom (Mindlin beam theory)
- Interface elements – two nodal degrees of freedom (zero thickness element)
- Rod elements – anchor, geo-reinforcement or prop

Structural element – beams

- Beams in 2D = Walls in 3D
- Bending and normal stiffness per running meter
- Predefined types of cross section and materials
- Output: bending moment, normal and shear force, deflection



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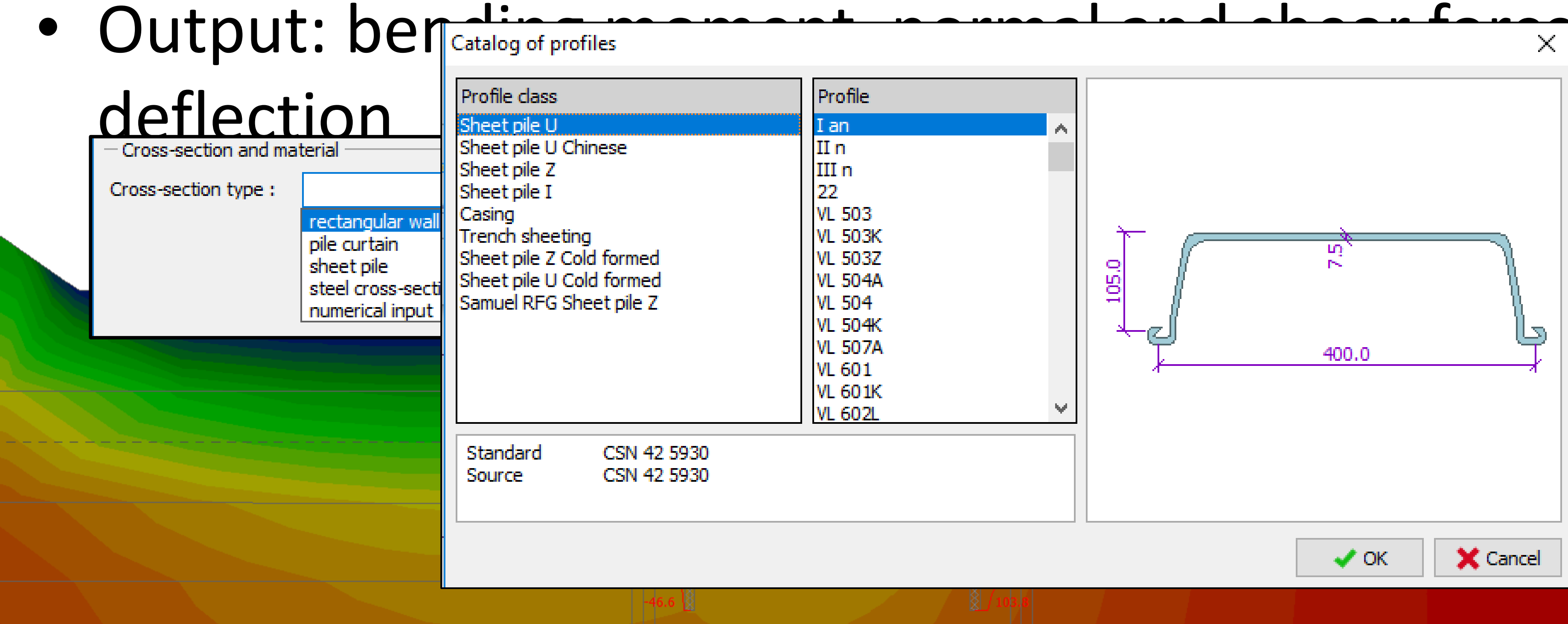

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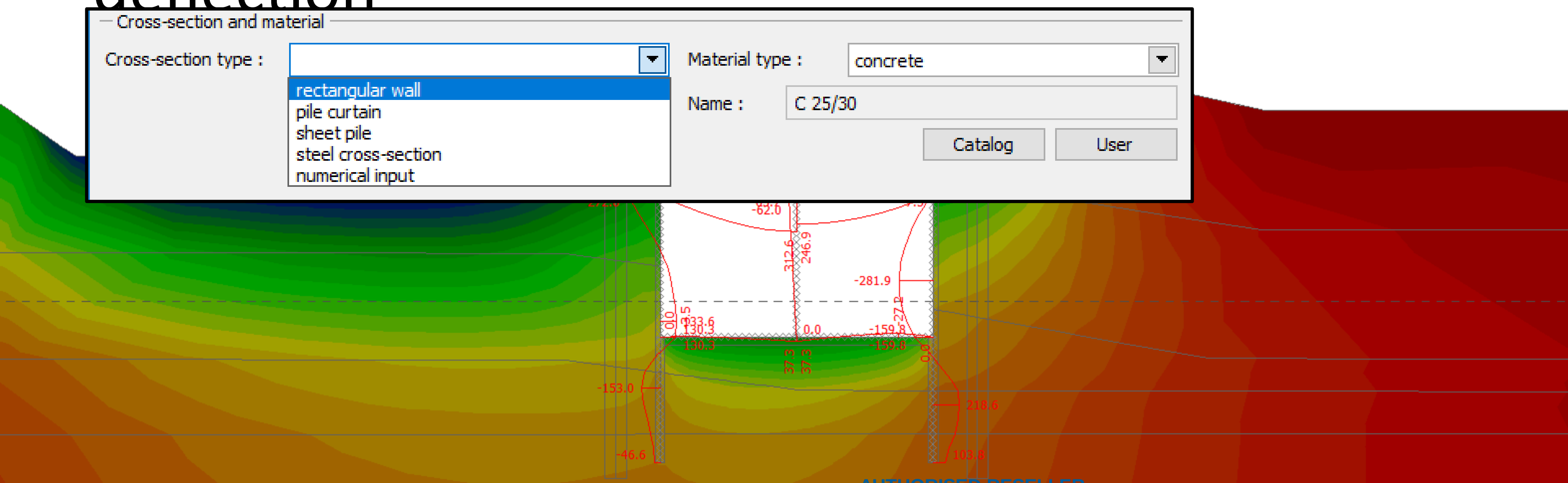

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Structural element – beams

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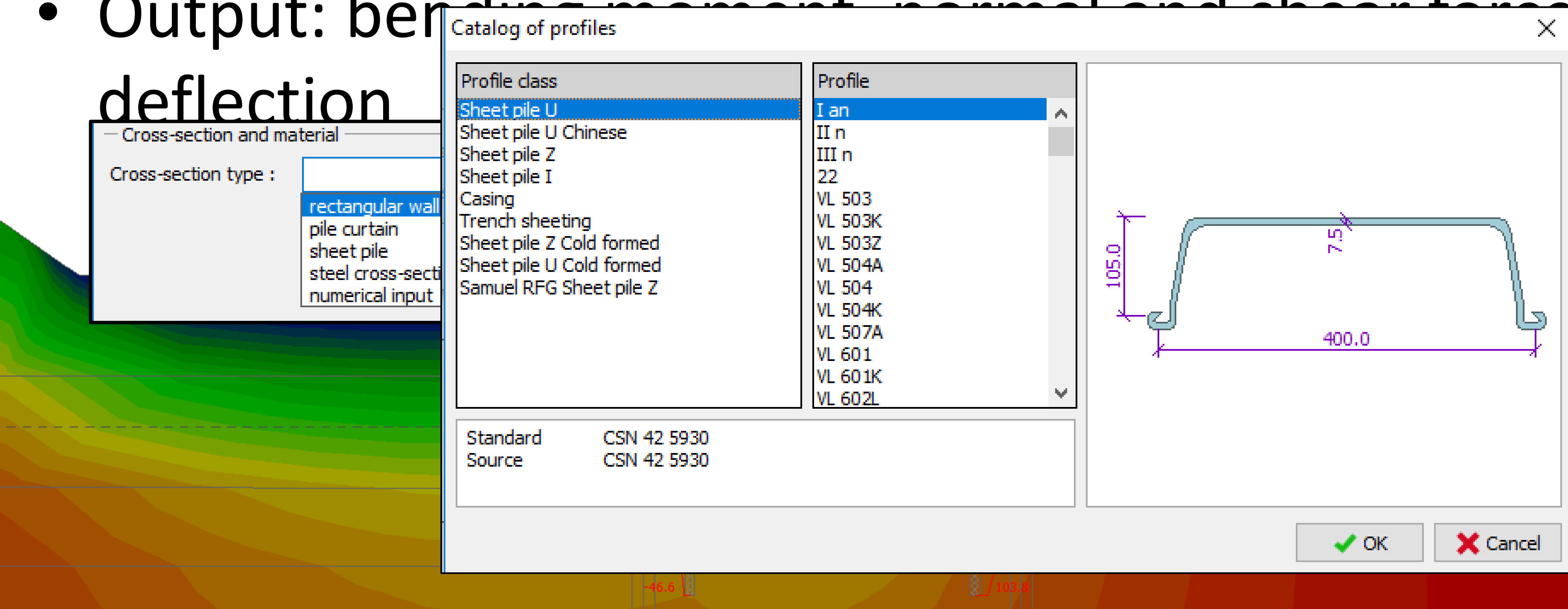
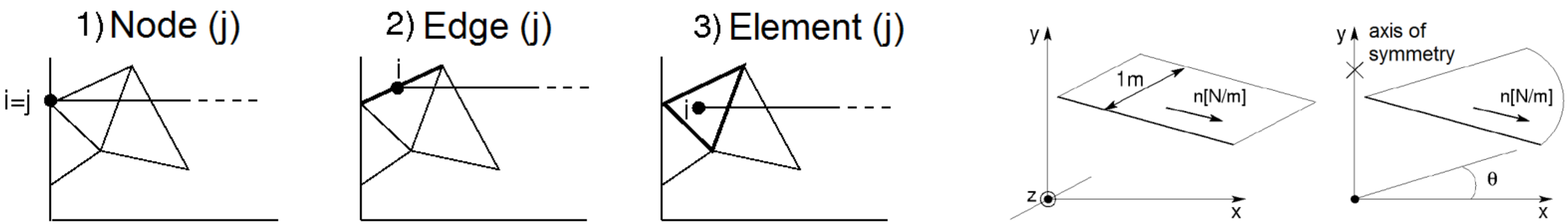
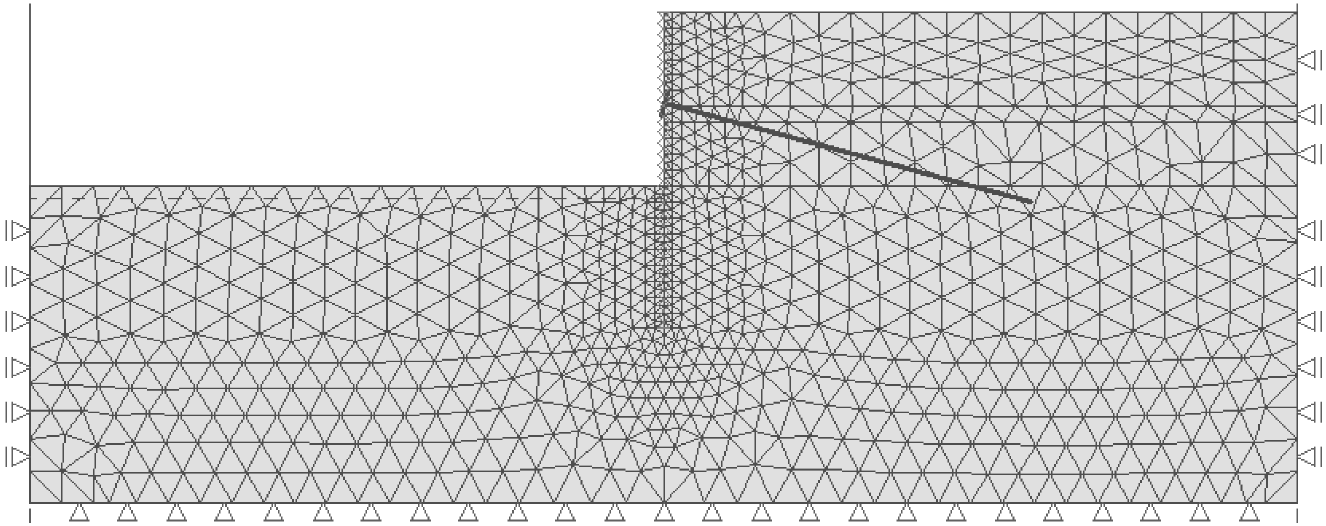


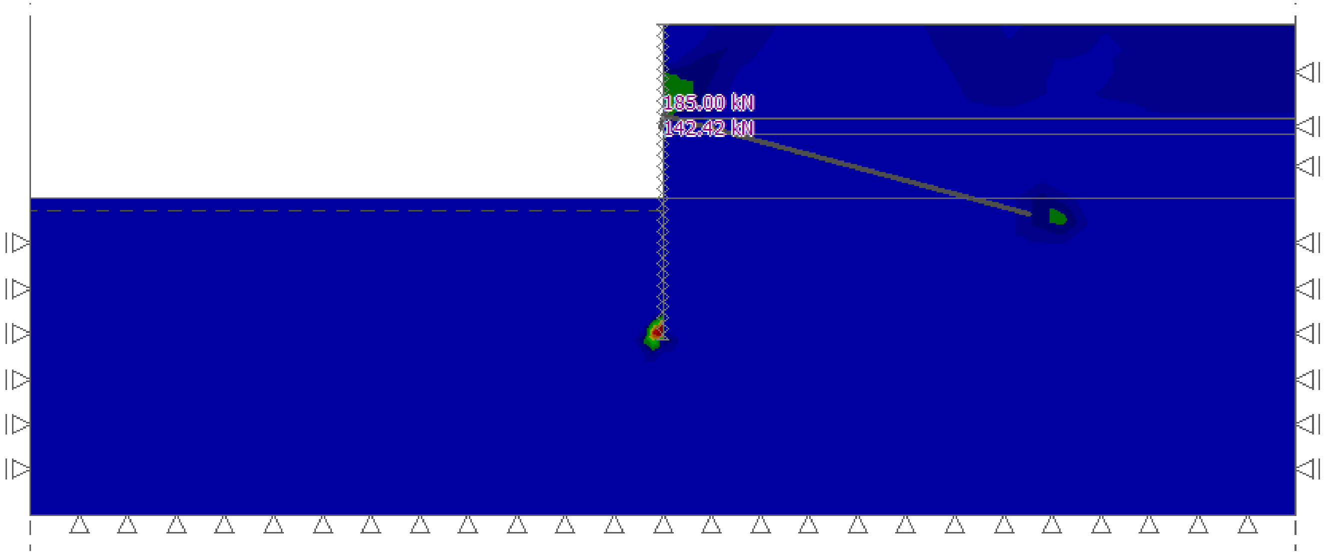
Structural elements – anchors

- Pre-stressed rod elements
- **Free elements**, not connected to FE mesh,
  - independent on topology, add at any stage
- Defined by
  - Pre-stress force, tensile strength, tensile stiffness



Structural elements – anchors



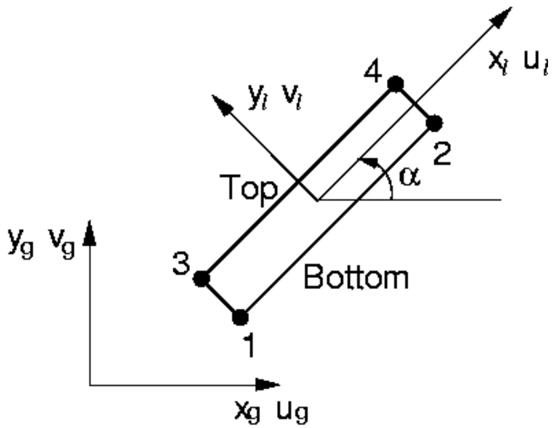


Structural elements - reinforcements

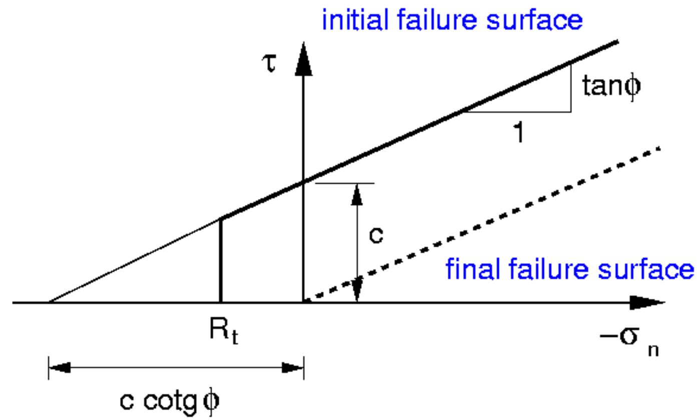
- Geotexiles, geogrids

Contacts

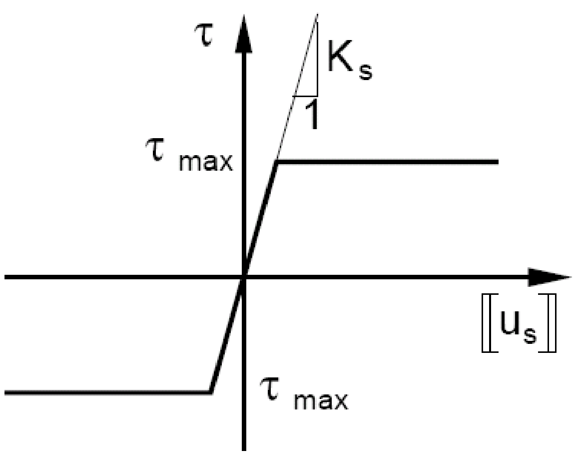
Contact element

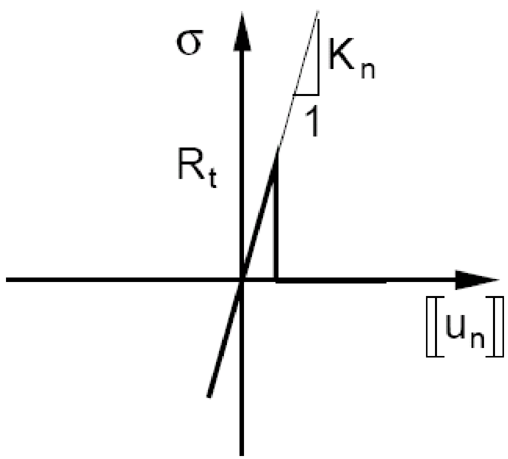


Mohr-Coulomb failure criterion



Initial stiffness



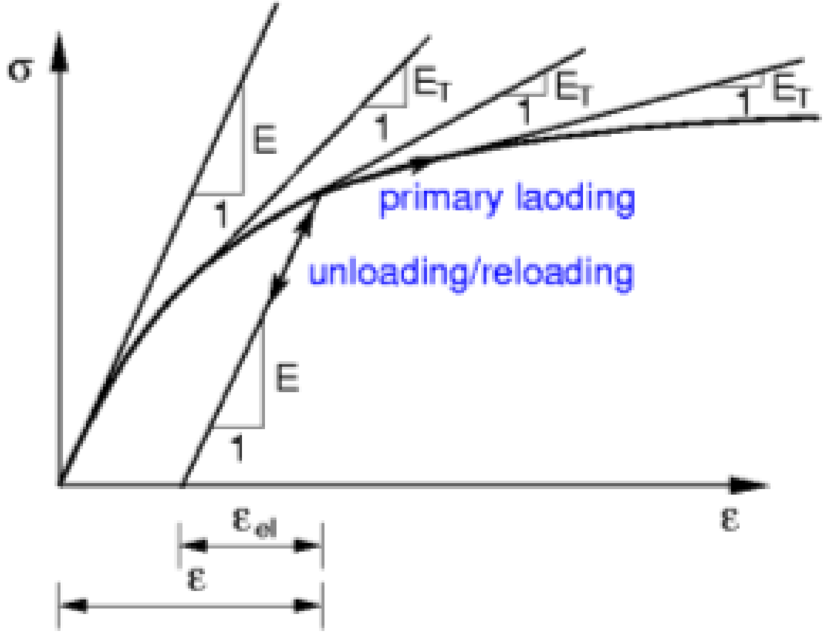


$$\left\{ \begin{array}{c} \tau \\ \sigma \end{array} \right\} = \mathbf{D} \left\{ \begin{array}{c} [\![u]\!]_l \\ [\![v]\!]_l \end{array} \right\}$$

$$\mathbf{D} = \left[\begin{array}{cc} K_s & 0 \\ 0 & K_n \end{array} \right]$$

Constitutive models

- Define **stress-strain relationship**



- Elastic models
- Elasto-plastic models of Mohr-Coulomb family
- Models of critical state

Elastic model

- Elastic model – Hooke's law

  Constant stiffness, E, ν

  Infinite strength

  Numerically stable

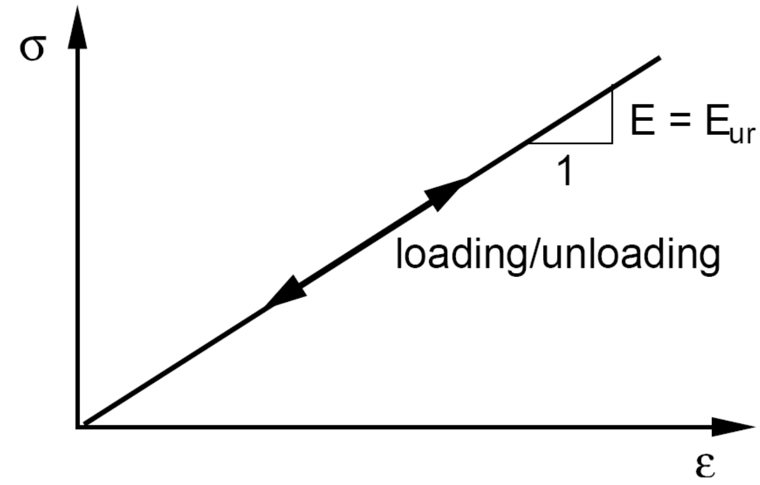
- Modified elastic model

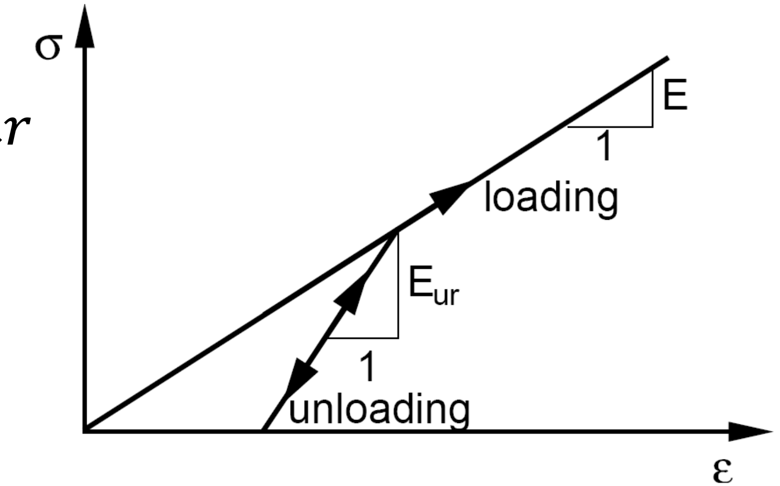
  Initial loading modulus E

  Unloading/reloading modulus E_{ur}

  Rule of thumb:

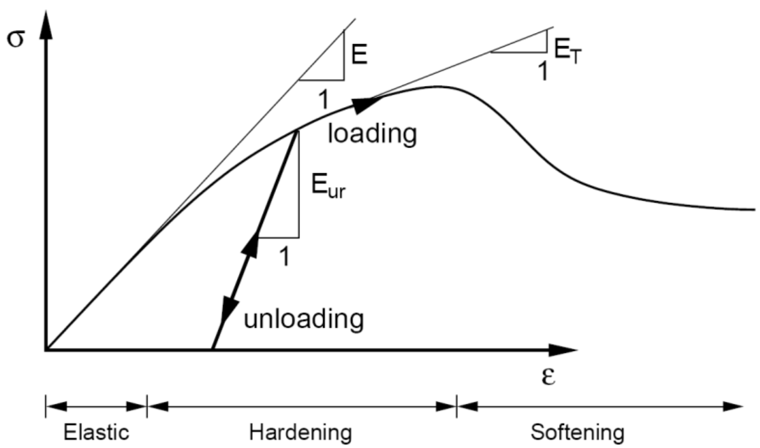
  $$E_{ur} = 3E$$

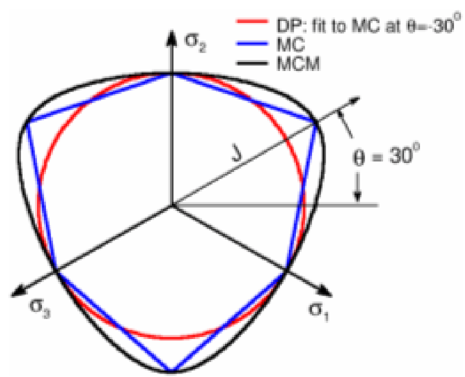




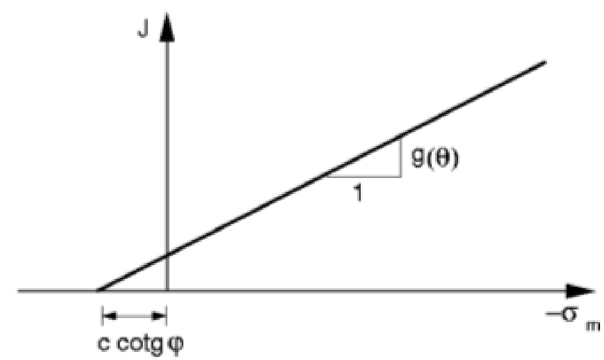
Mohr-Coulomb family of models

- Elasto-plastic models
- Elastic region given by yield surface in stress space
- Constant stiffness in elastic region
- Limit deviatoric stress J increases with compressive mean stress $-\sigma_m$





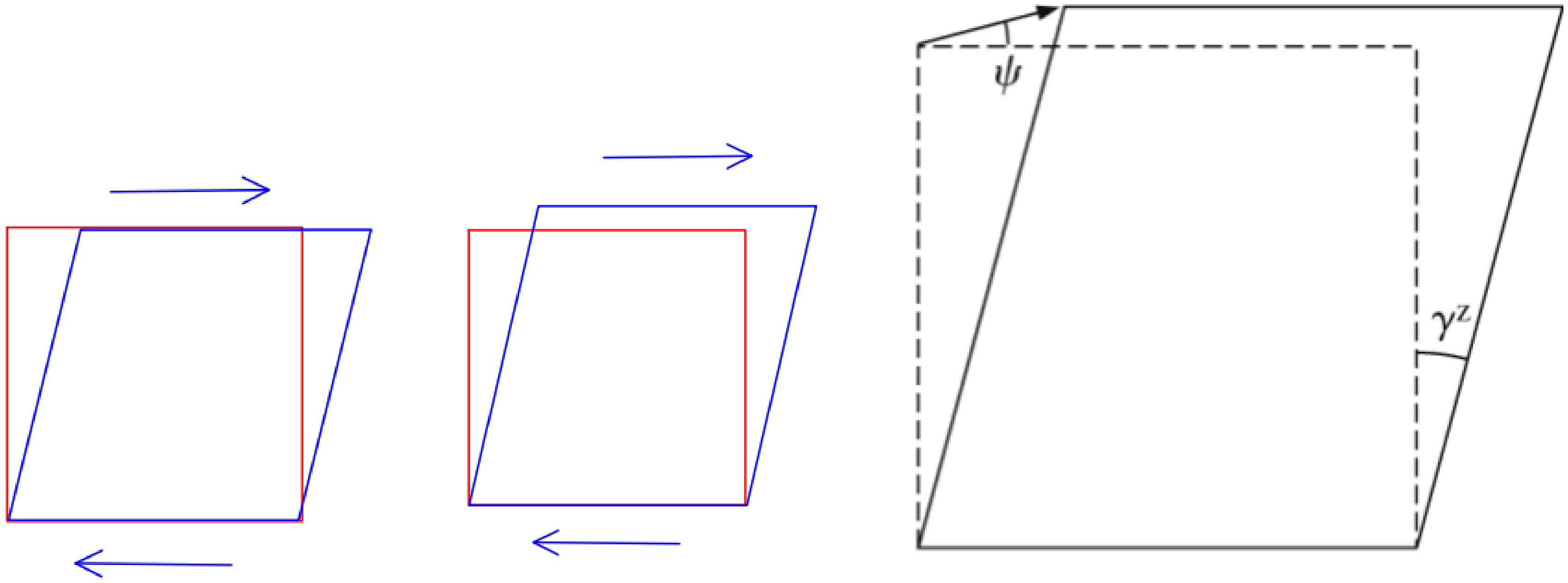
(a)



(b)

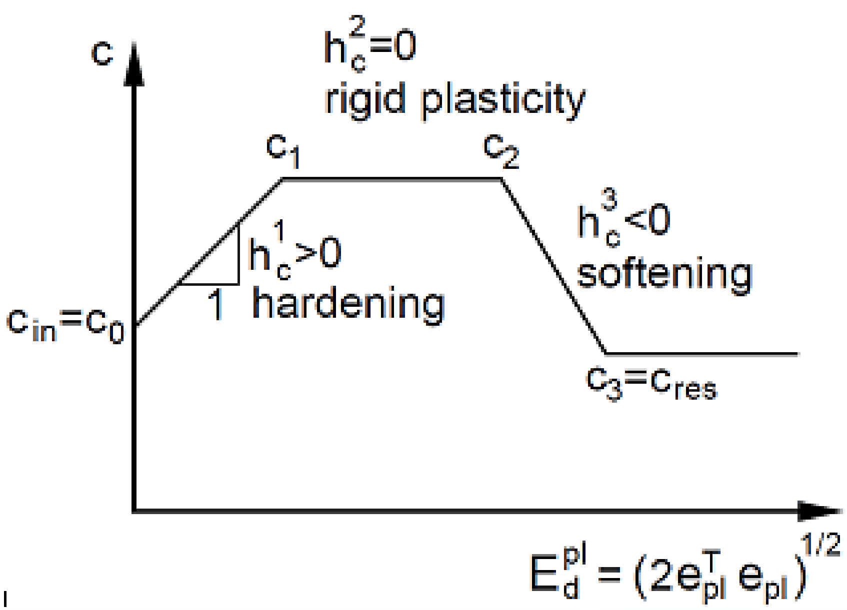
Angle of dilatancy

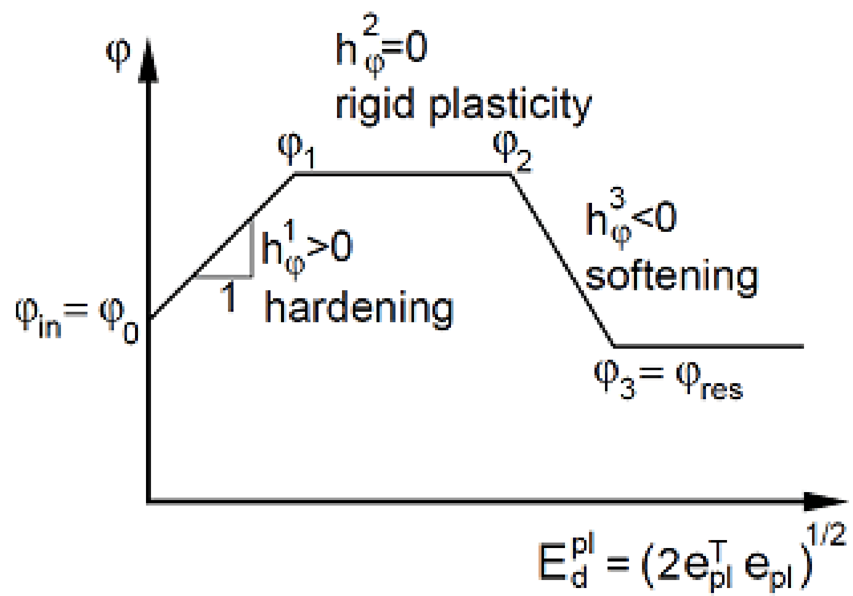
- Controls the volumetric plastic strain
- Dense soil tend to dilate
- Default value $\psi = 0°$
- Typical range $\psi = \langle 0°, 5° \rangle$



M-C hardening/softening

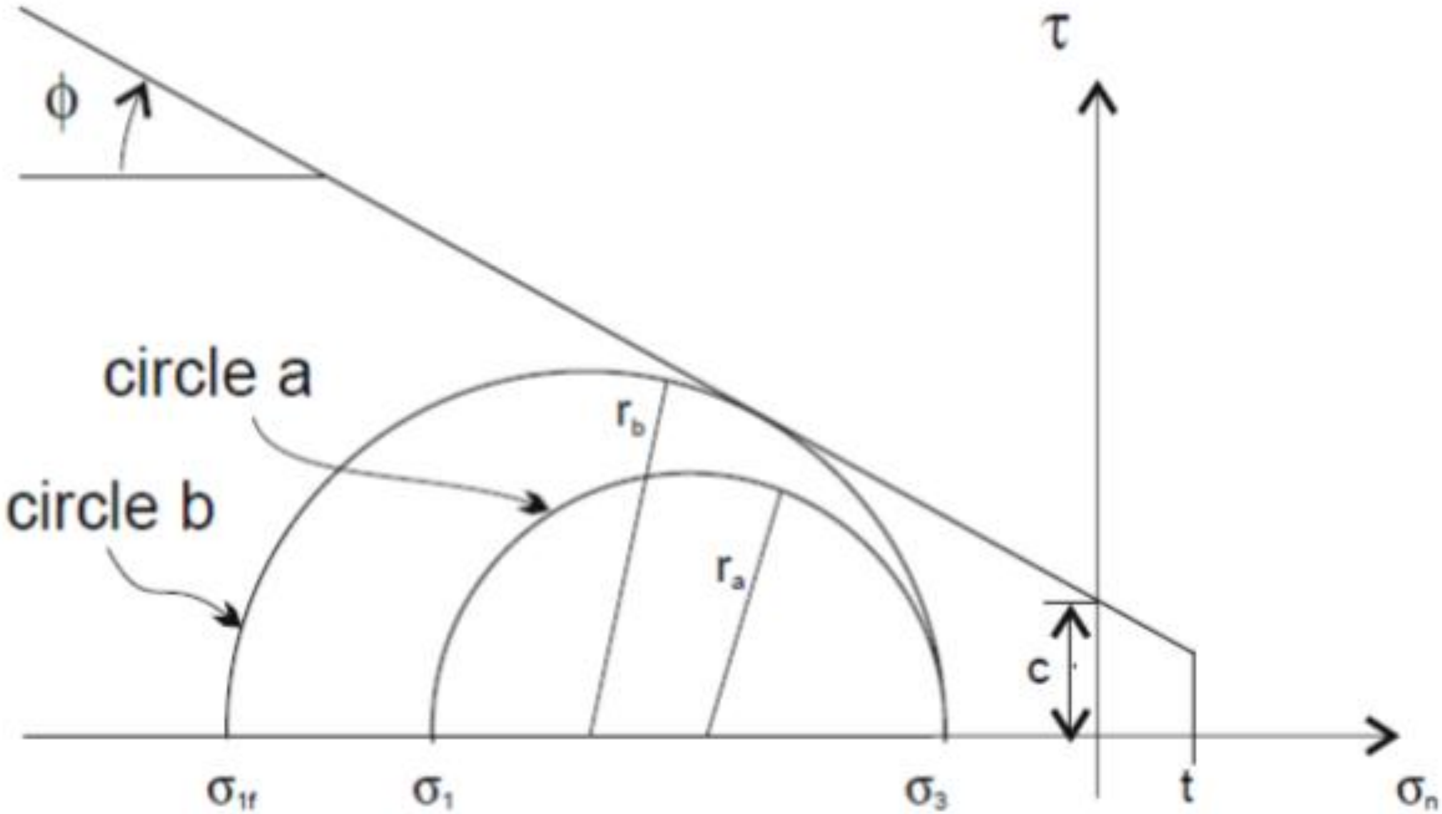
- Advanced material model feature
- Strength parameters depend on plastic strain
- $\varphi = \varphi(E_{d,pl}), c = c(E_{d,pl})$
- Defined as piecewise linear function





Tension cutoff

- Limits the tensile stress that is allowed due to cohesion

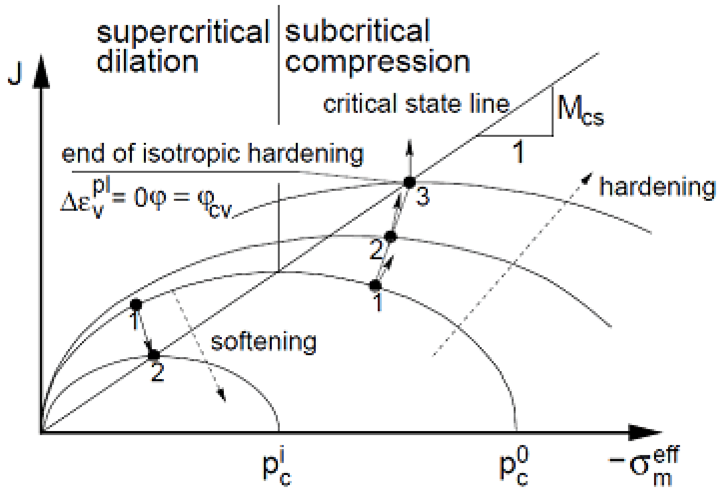


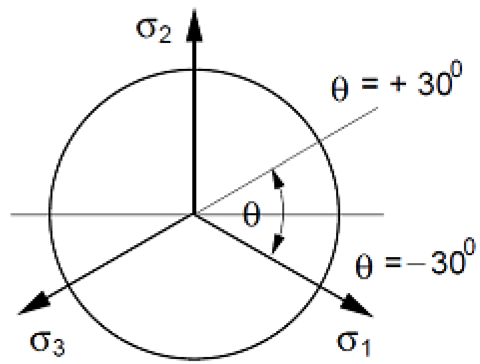
Critical state model

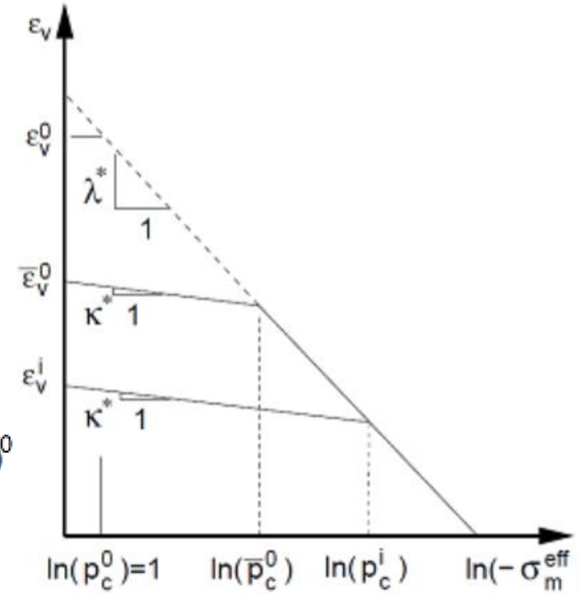
- They define “state” of the soil
  - Degree of „compactness“
  - Void ratio $e = \frac{V_p}{V_s}$
- Shearing of dense sand → dilatation
- Shearing of loose sand → compaction
- Stiffness depends on
  - Void ratio
  - Stress
- Non-standard material parameters, lab. tests

Critical state models

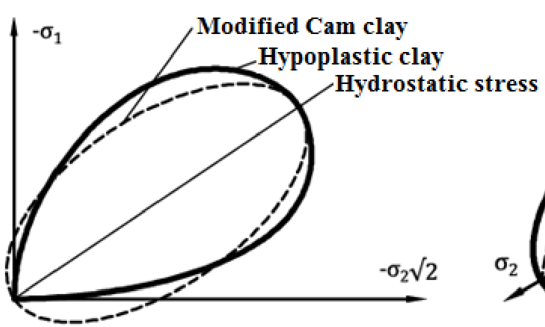
- Cam clay

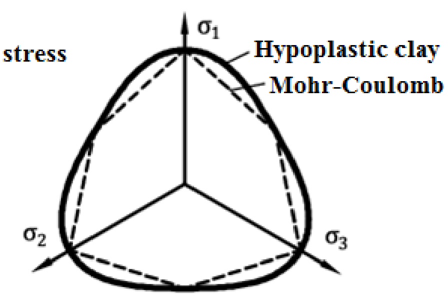


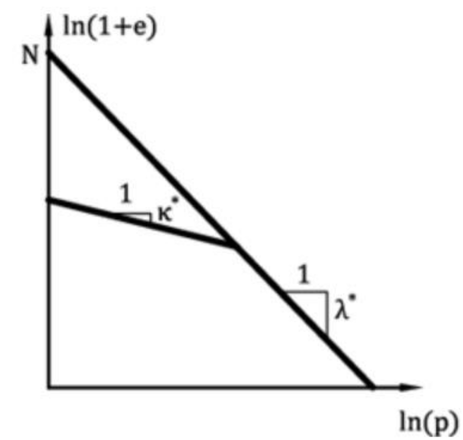




- Hypoplastic model for clay







Critical state models

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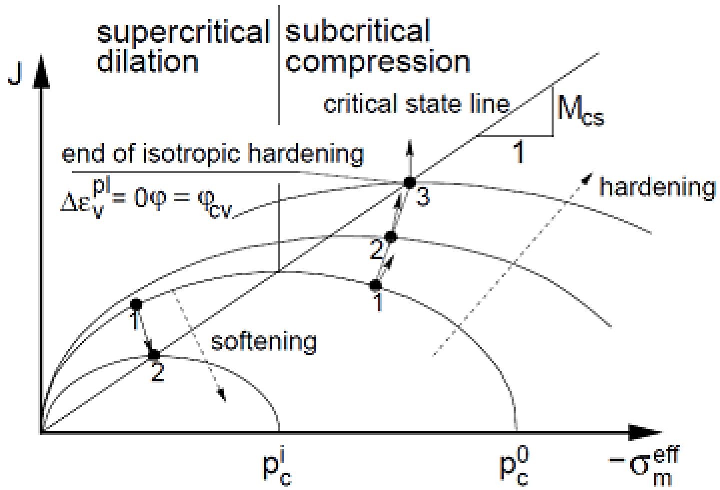

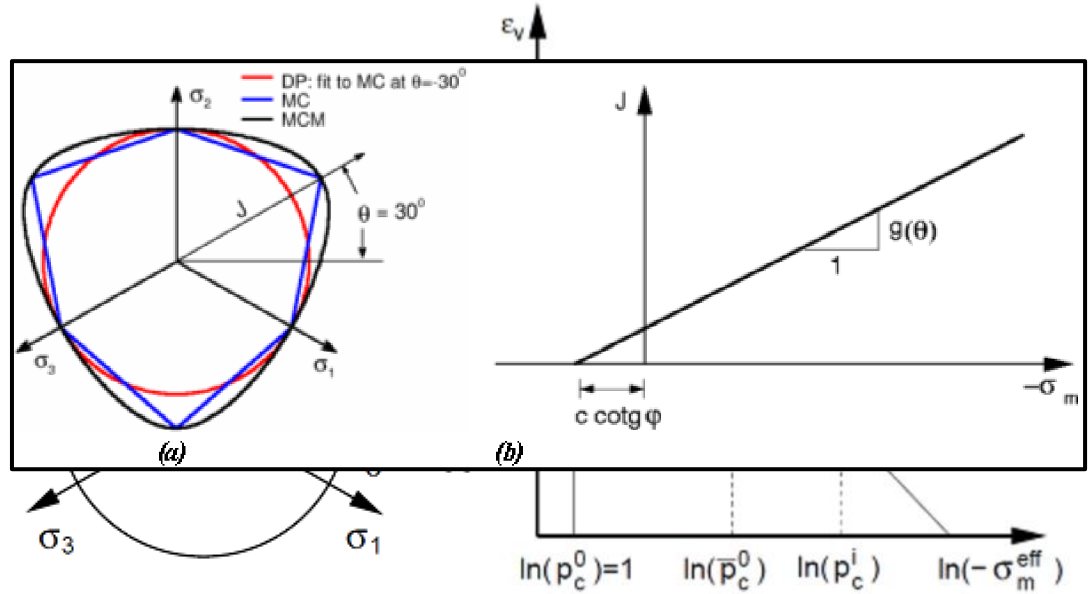

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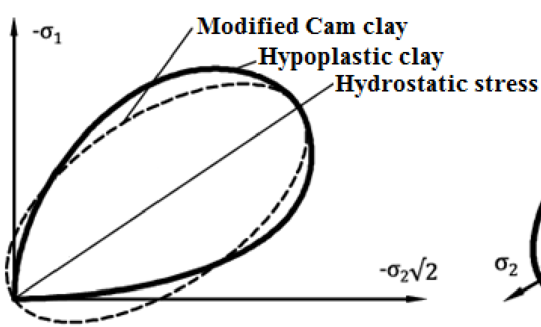
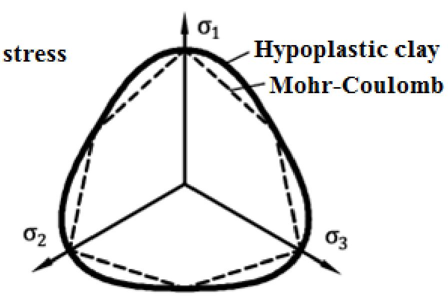
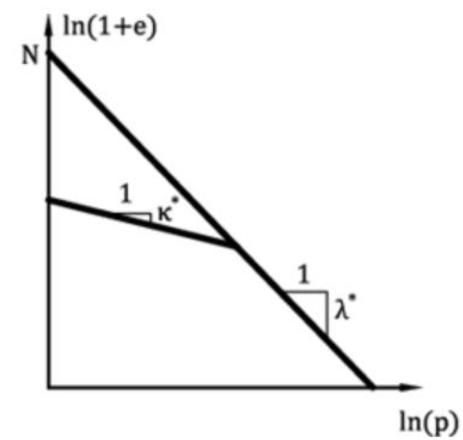






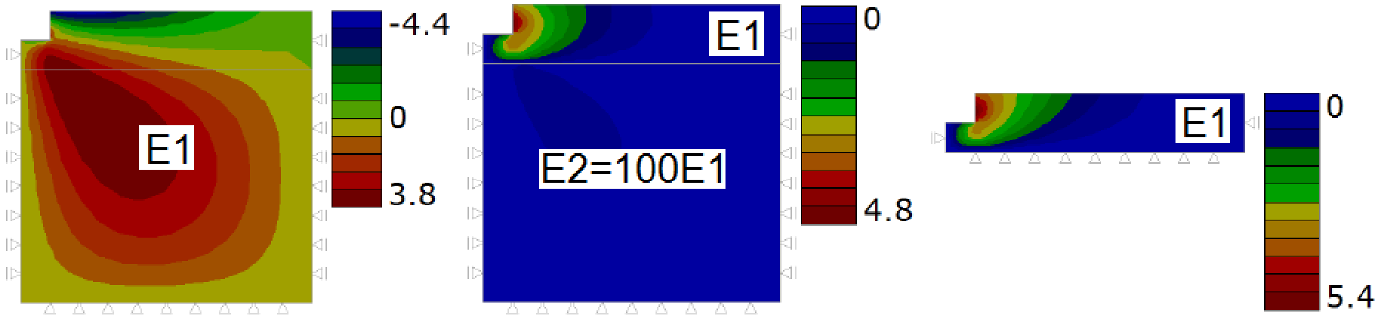
Constitutive models - application

- **Elastic model**
  - Linear stress/strain relation, infinite strength
- **Modified elastic model**
  - Unloading/reloading modulus, infinite strength
- **Mohr-Coulomb**
  - Shear failure, most standard model
- **Modified M-C, Drucker-Prager**
  - Smooth yield surface → better numerical stability
- **Critical state models**
  - Very loose/dense soil, significant volumetric strain

Effect of mode size

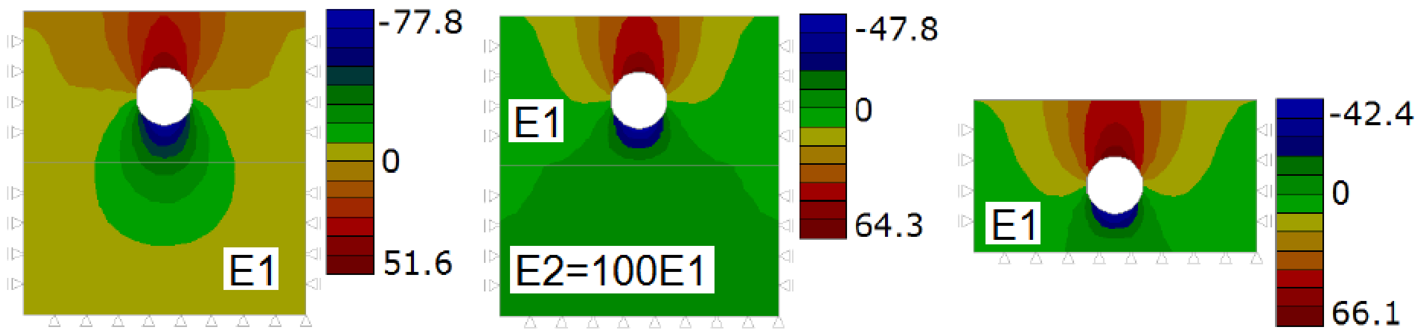
Simple elastic analysis of a shallow excavation

Plot of horizontal displacements



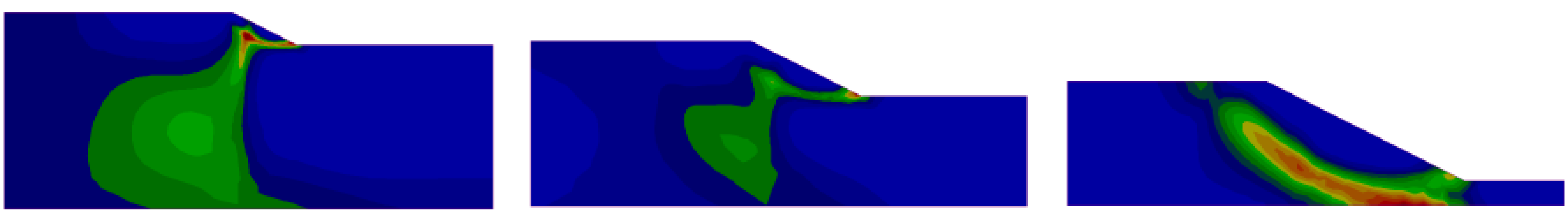
Elastic analysis of tunnel excavation

Plot of vertical displacements



Slope stability analysis

Plot of an equivalent plastic strain



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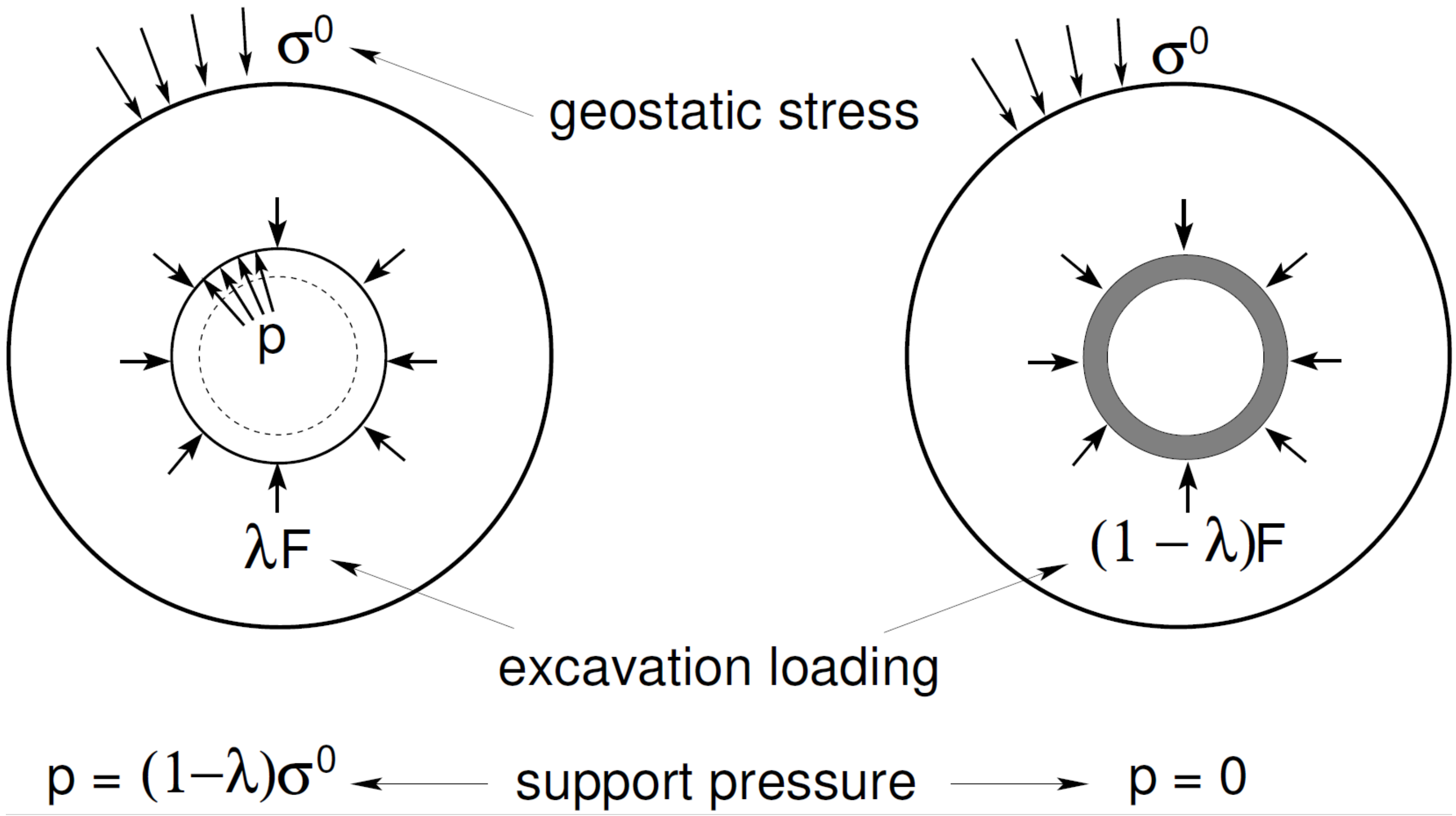
Driven tunnels

- How to model clearly 3D structure in 2D?
- Two limit states in 2D

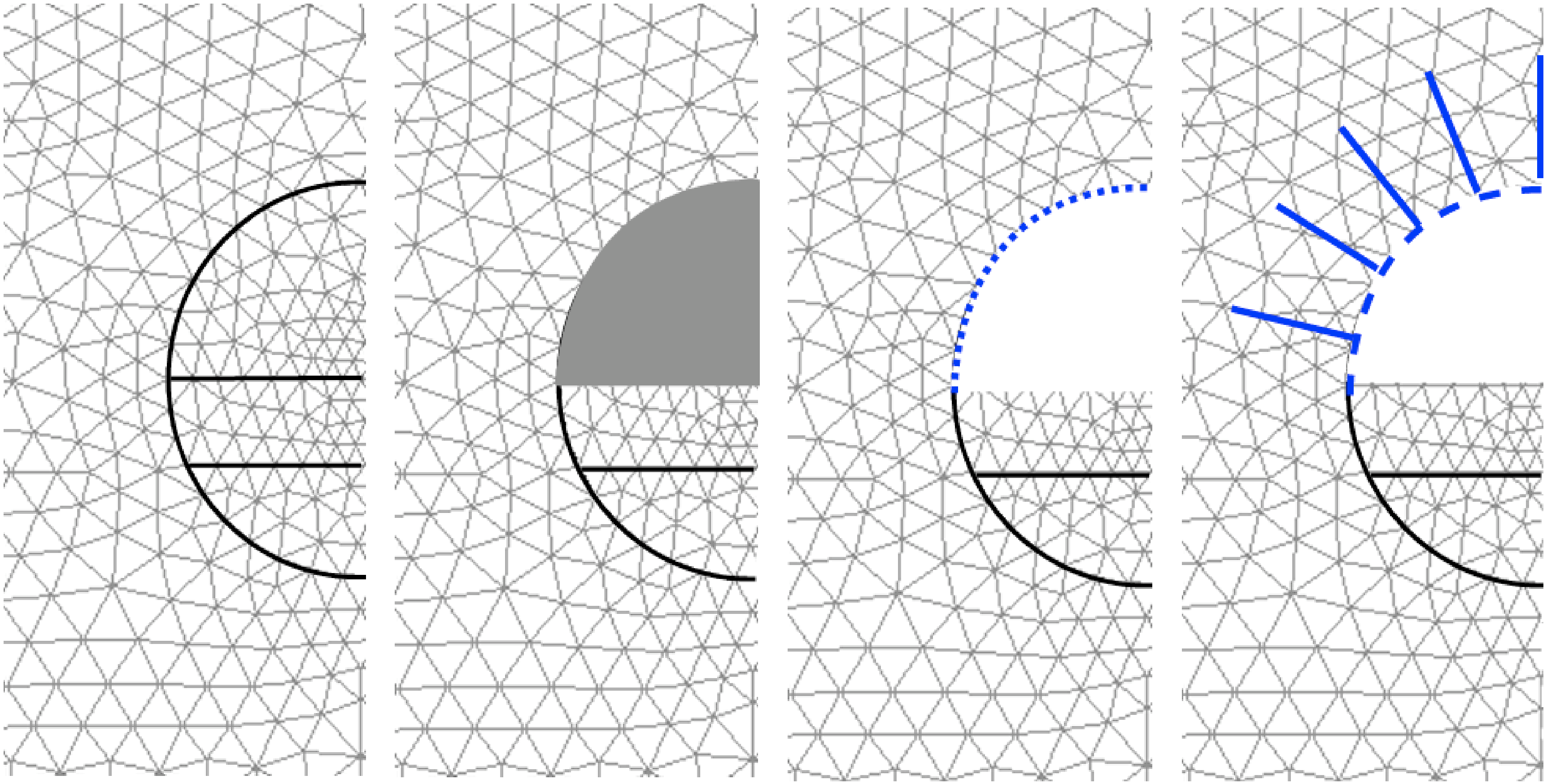
Driven tunnels

- Convergence confinement method (λ-method)
- This function is called “Excavations” in Geo5 FEM



Driven tunnels

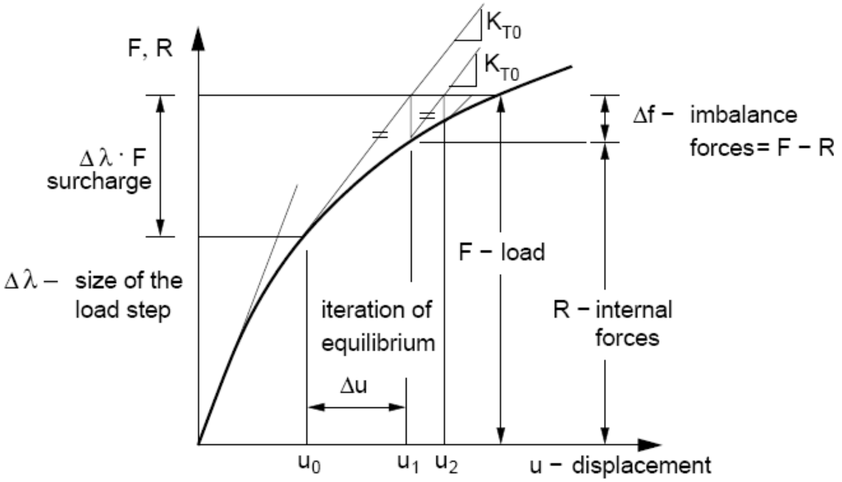
- Sequential application of “excavation forces”



Nonlinear solver

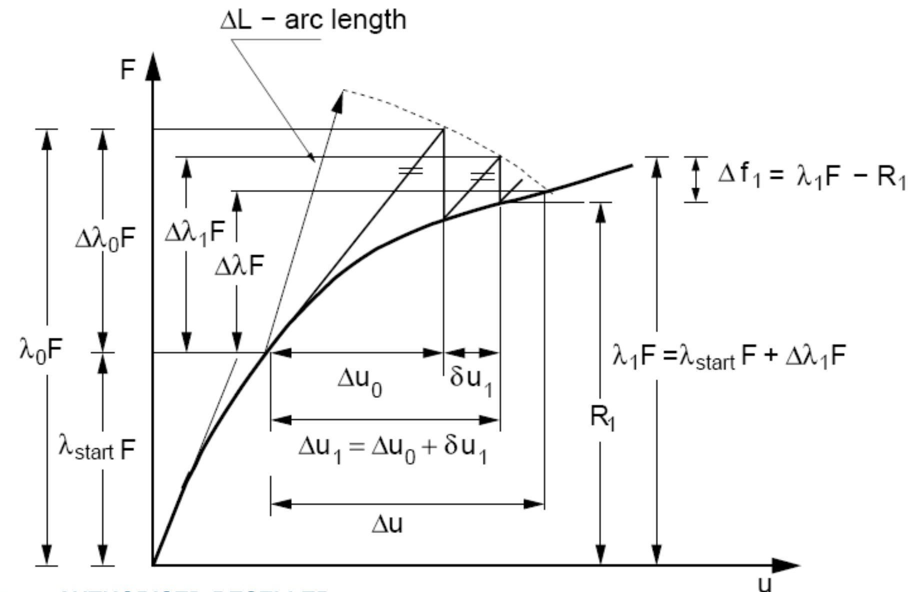
Newton-Raphson iteration scheme

- Most often used
- May fail when close to the limit load
- May fail when the load increment is too large



Arc-length method

- Useful when searching for the maximum or limit load
- In general more time consuming
- May fail when the load increment is too large



Both methods can be combined with the Line search method to stabilize the iteration process

EISEKO COMPUTERS S.R.L.

Viale del Lavoro, 17
37036 S. Martino B.A. (VR)
tel. + 39 045 8031894
www.eiseko.it

Tel. 045 8031894

support@eiseko.com

Assistenza Remota