CG 26
3D ASPECTS OF NATM TUNNELLING

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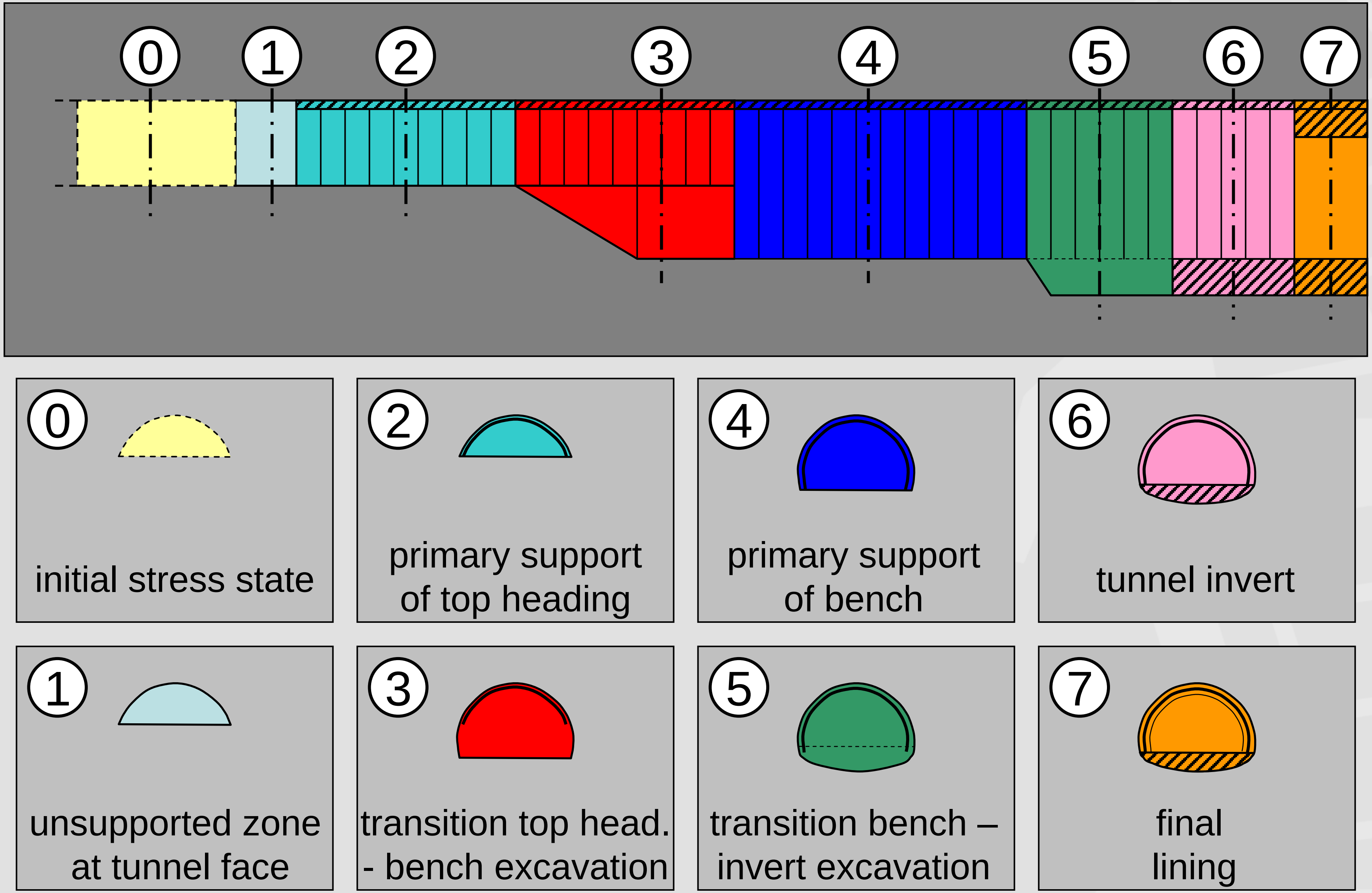
CONTENTS

INTRODUCTION

- **3-D Models**
  - **easy modelling of excavation sequence**
  - **computational effort high**
  - **essential for analysis of face stability**

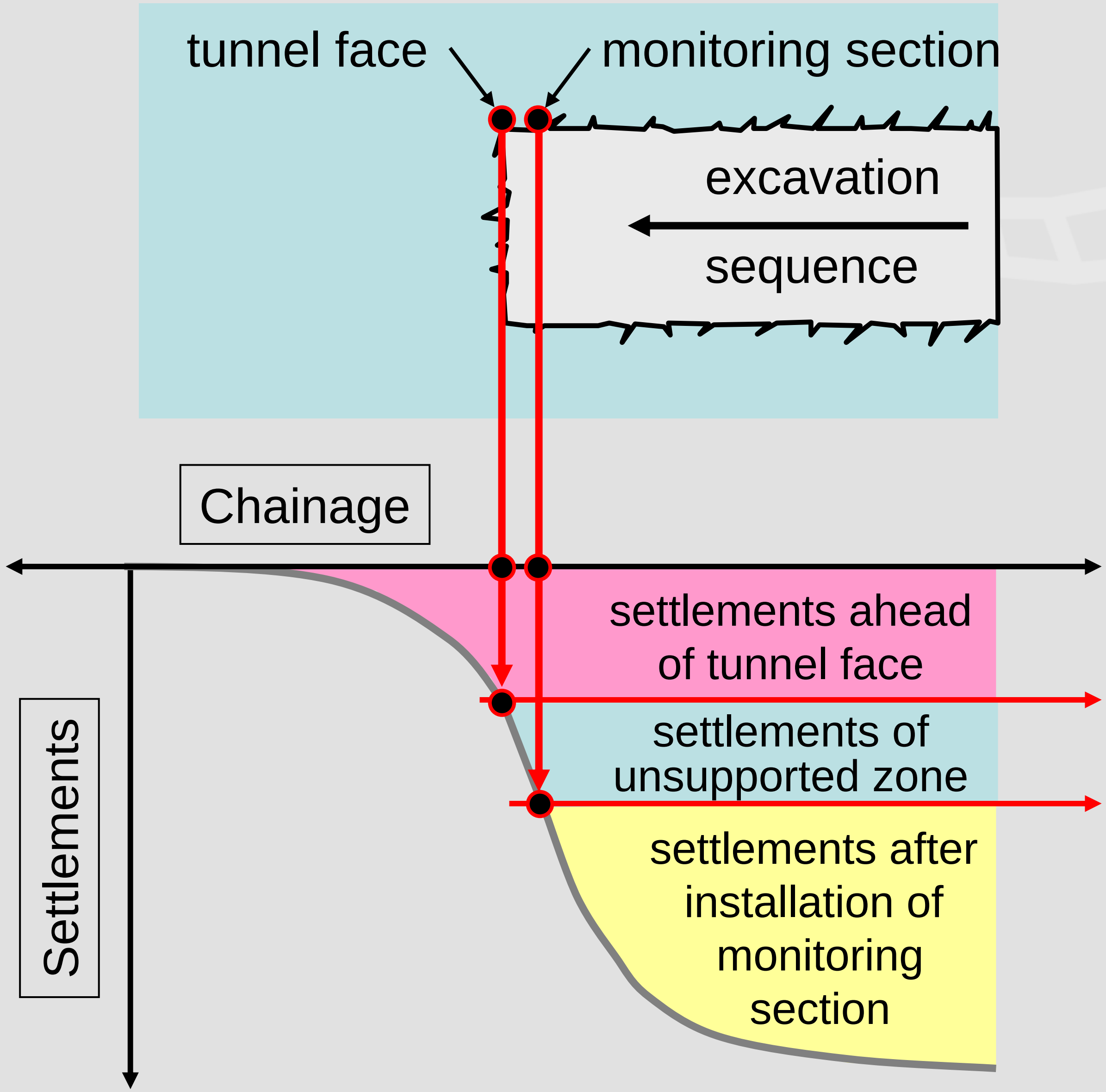
- **Plane Strain**
  - **assumption of pre-relaxation factors**
  - **excavation sequence in cross section**
  - **face stability cannot be considered**
  - **"state of the art" in practice**

TYPICAL NATM EXCAVATION

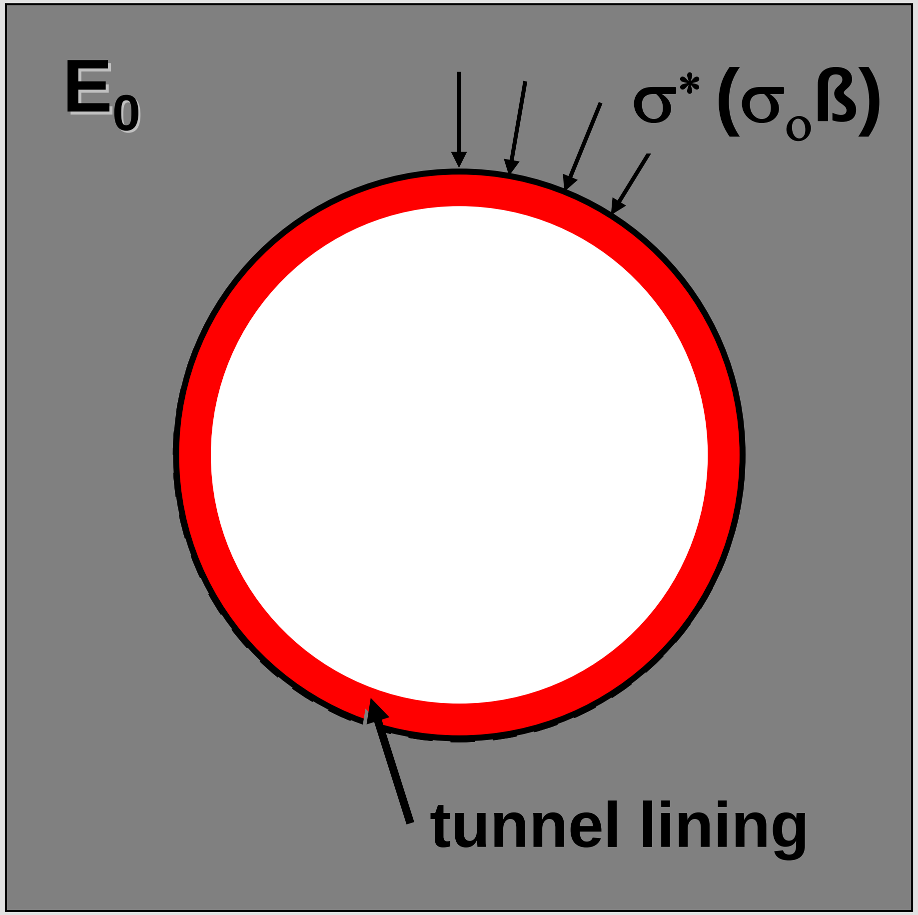


EXAMPLE OF STAGED EXCAVATION

DEFORMATION AHEAD OF FACE



2D MODELLING - LOAD REDUCTION METHOD



EXCAVATION

approximate values for β :

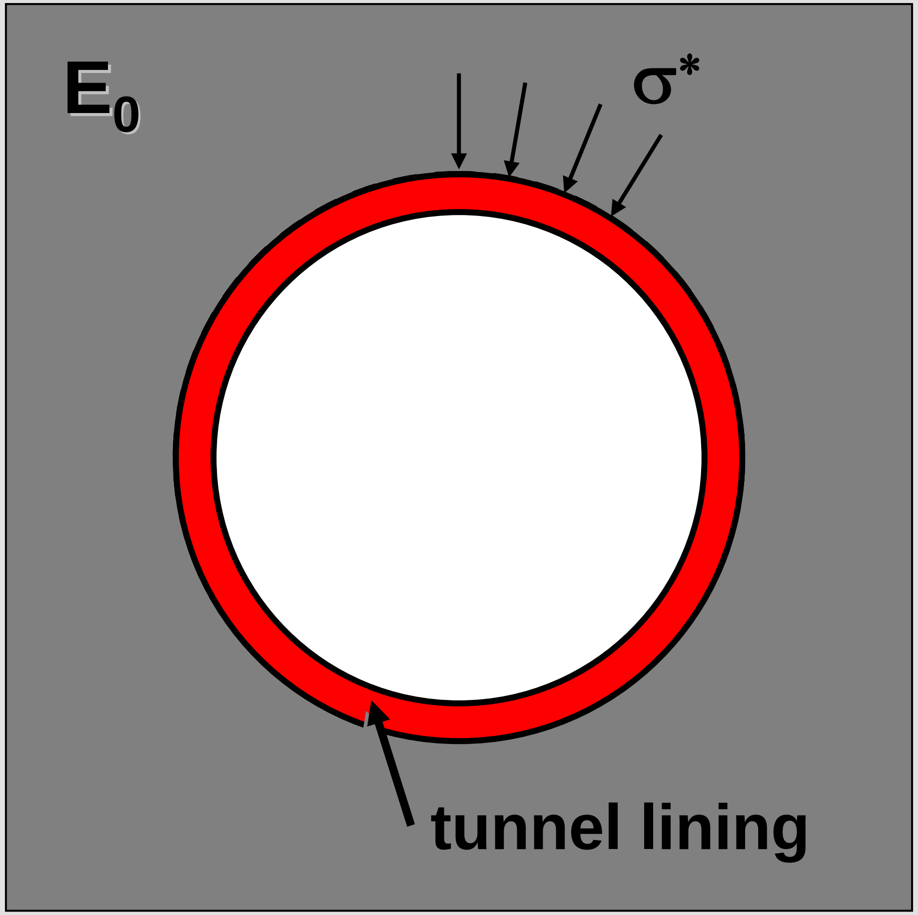
β = 0.2 – 0.5
for top heading excavation

β = 0.4 – 0.8
for side drift excavation

(Laabmayr & Swoboda 1986)

PLAXIS: Mstage 1- β

2D MODELLING - STIFFNESS REDUCTION METHOD



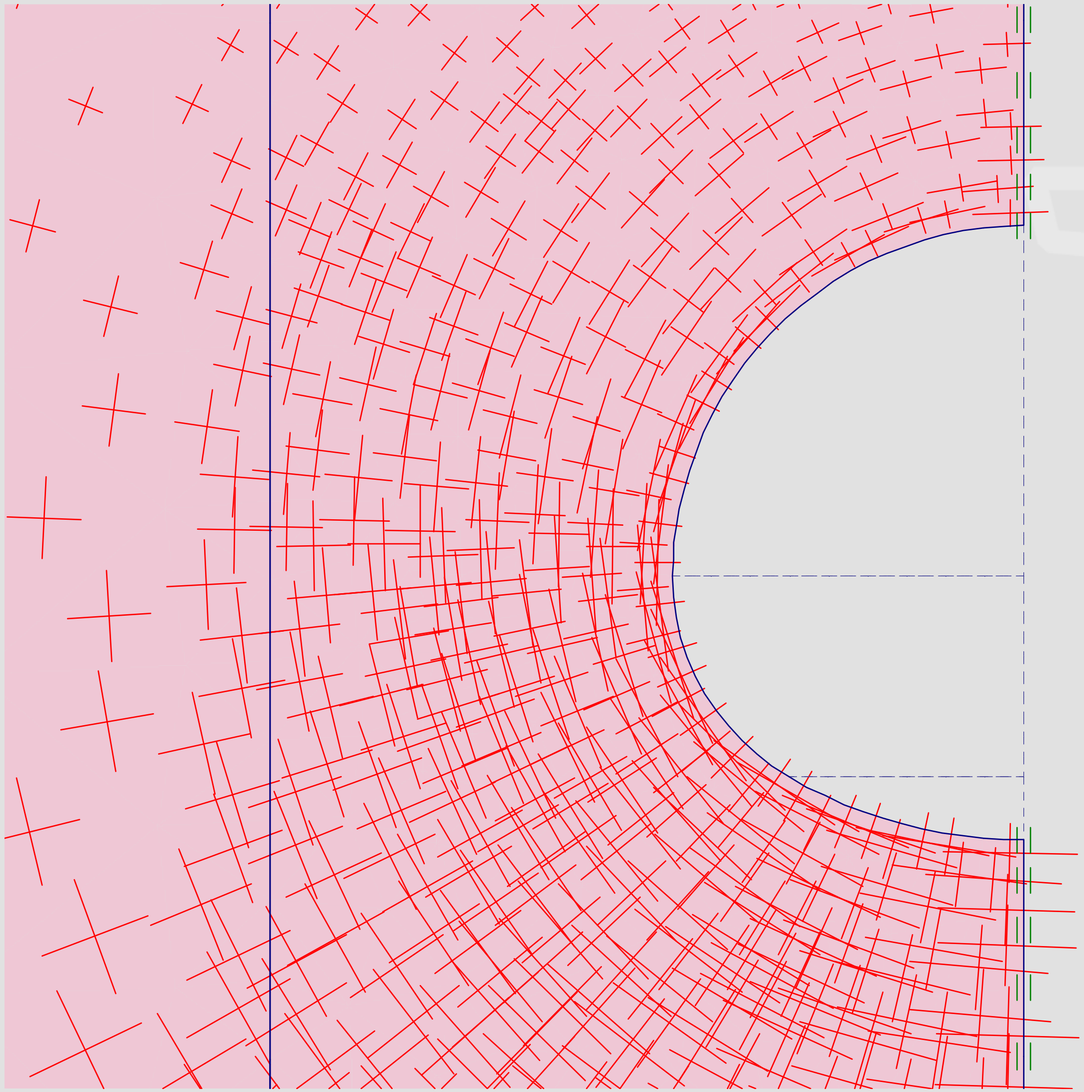
EXCAVATION

approximate values for α :

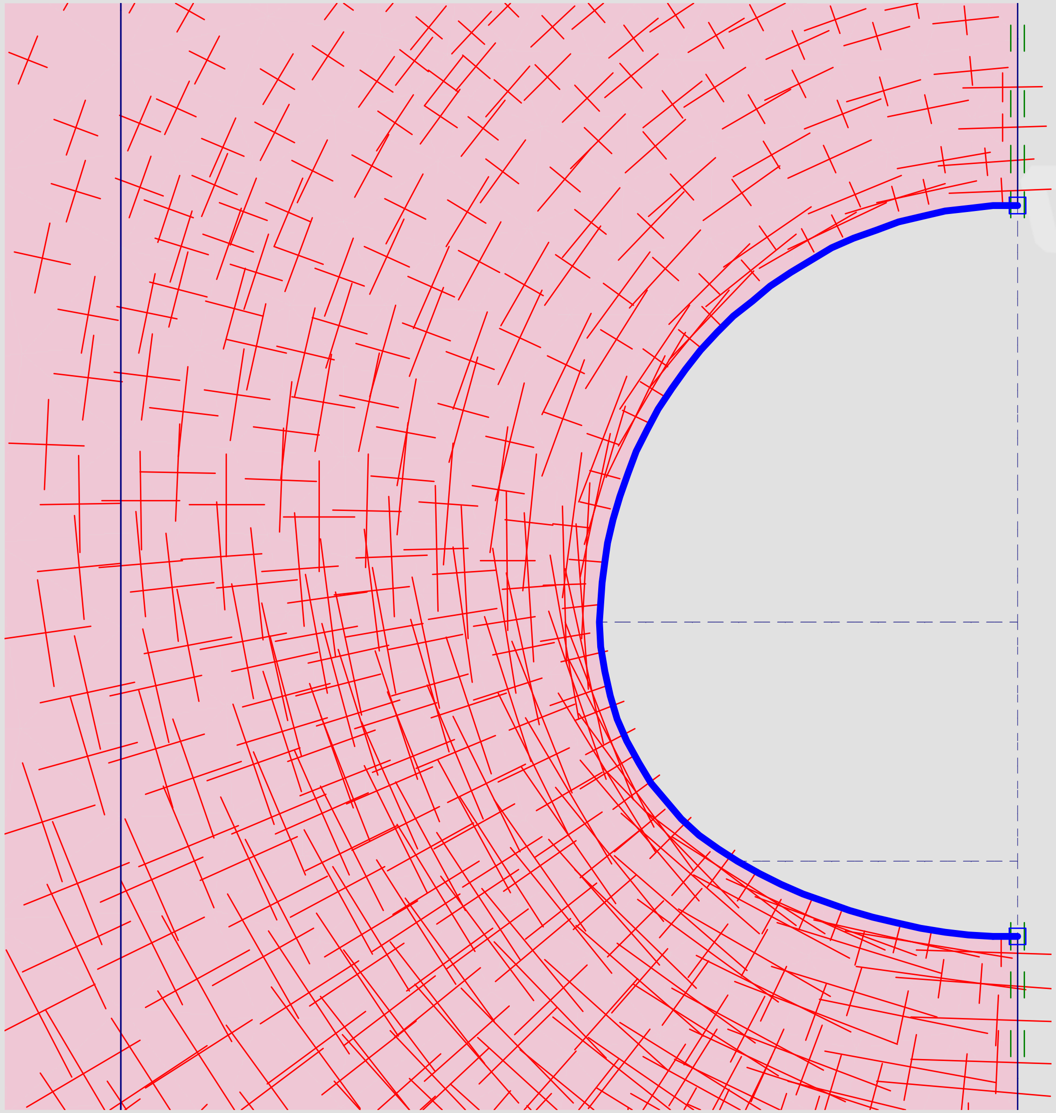
$\alpha = 0.3 – 0.5$

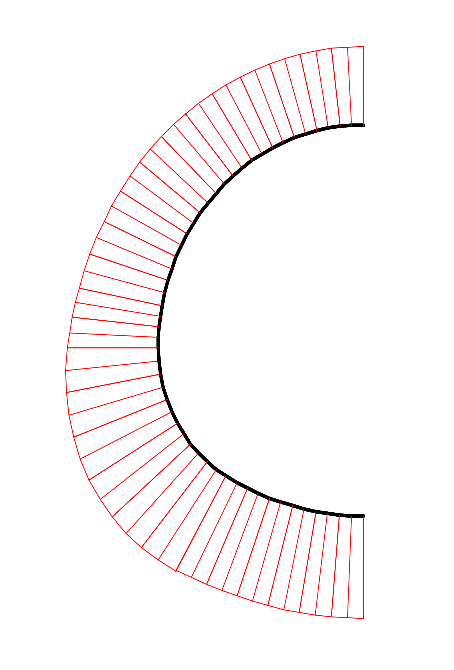
(Schikora & Fink 1982)

PRE-RELAXATION

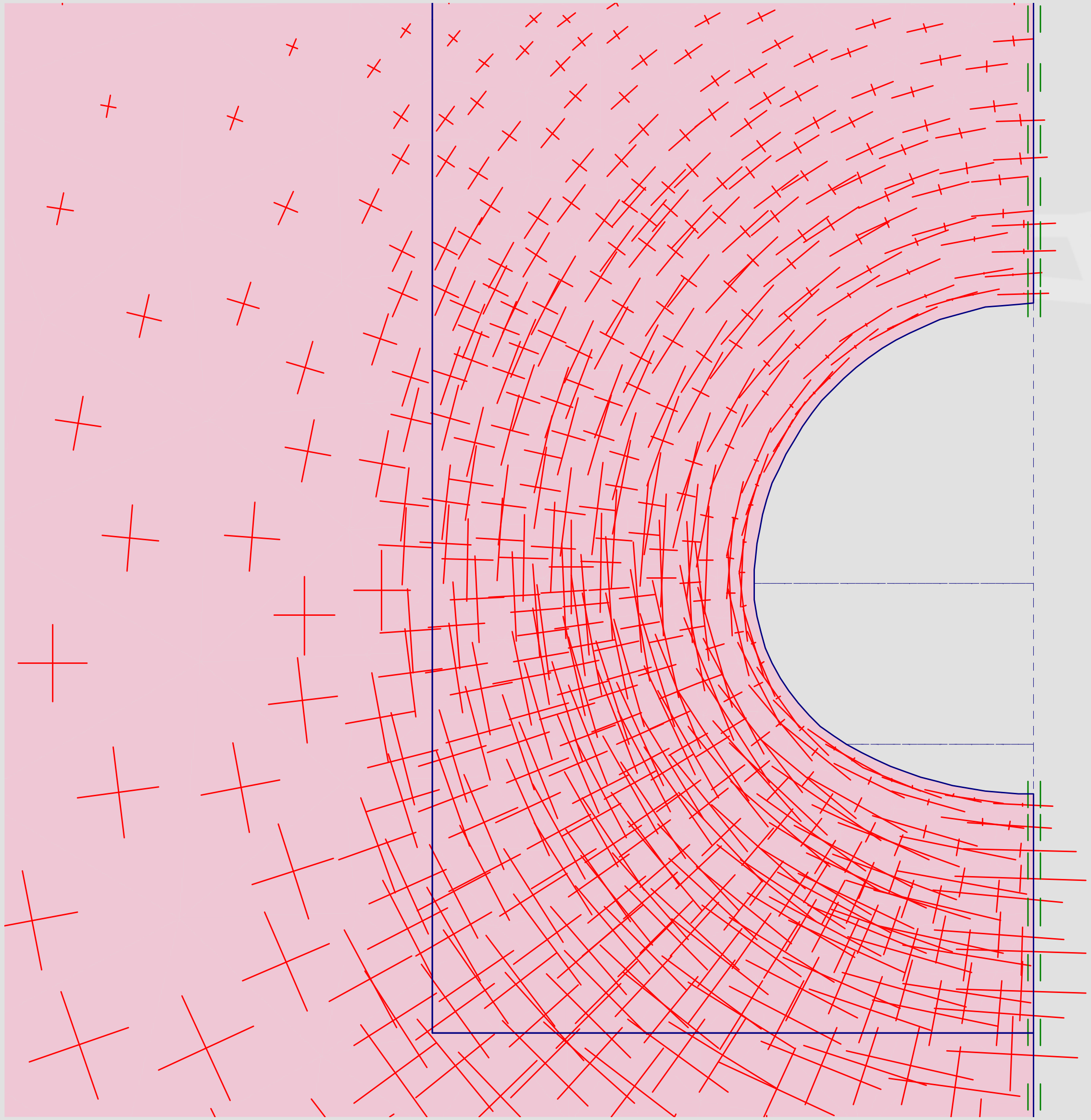


FULL EXCAVATION WITH LINING

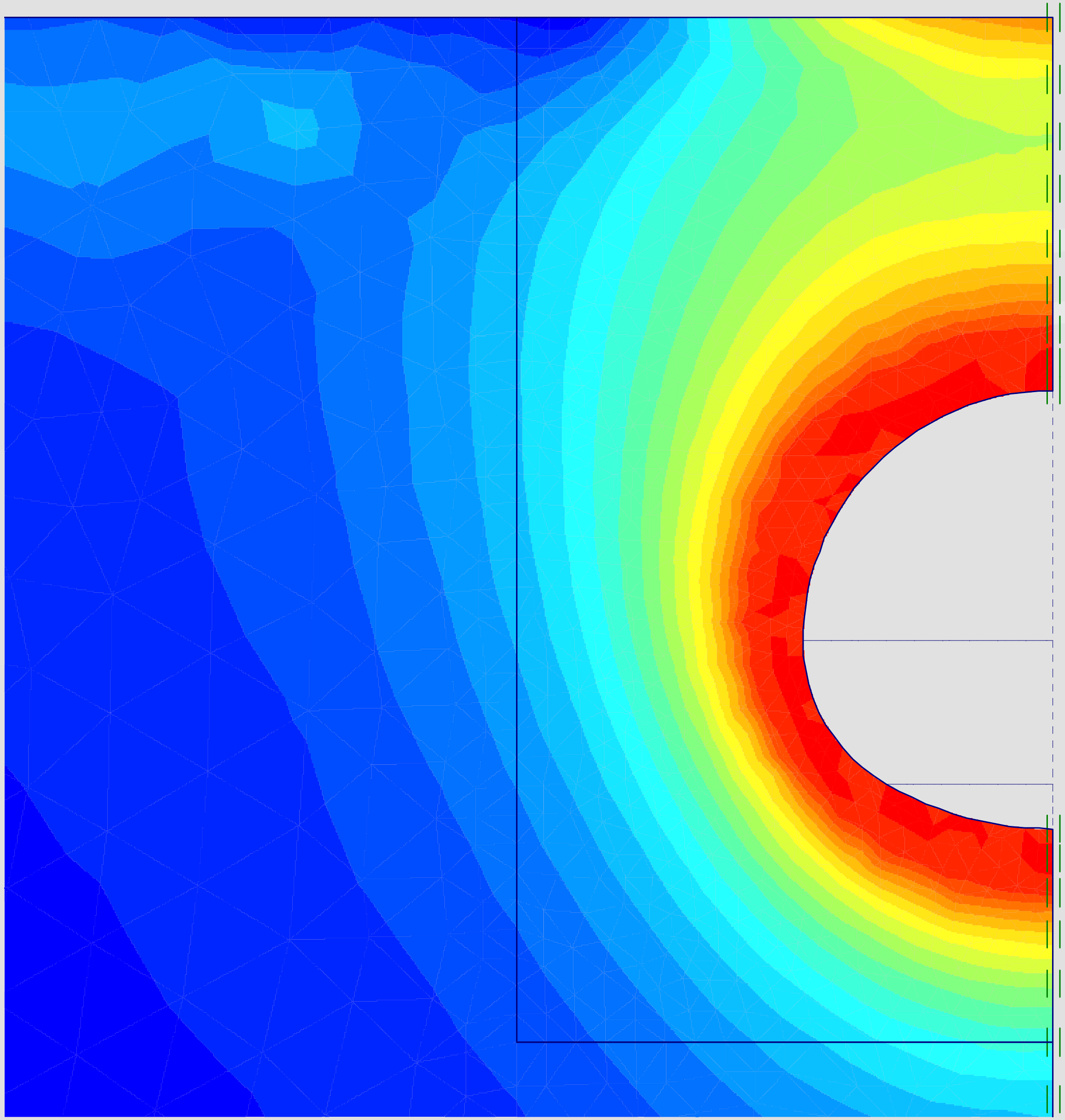




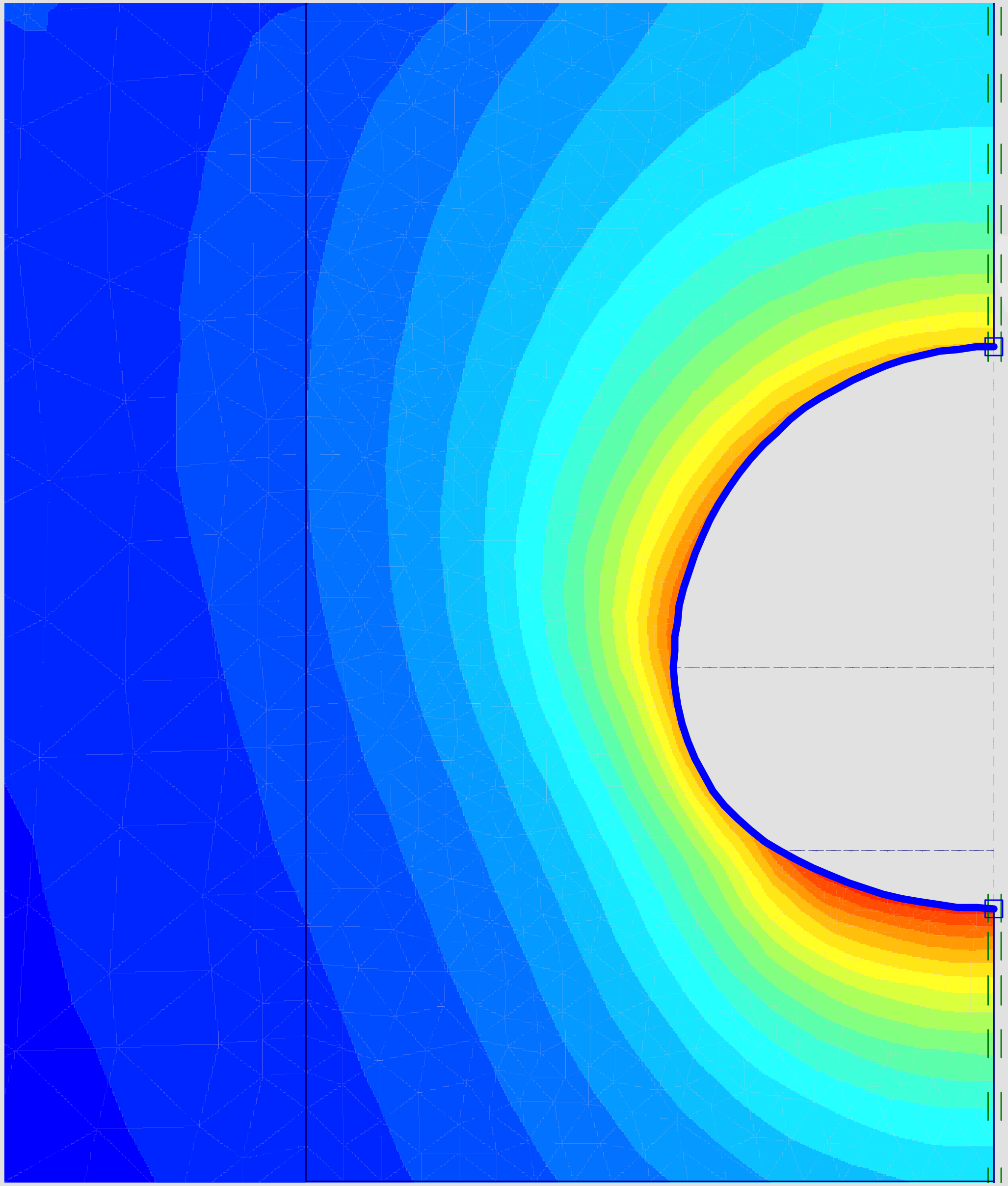
FULL EXCAVATION WITHOUT LINING



"PLASTIC ZONE" WITHOUT LINING



"PLASTIC ZONE" WITH LINING



CHOICE OF α AND β

- values depend on:
  - ground conditions
  - length of unsupported section
  - advance rate
  - time of construction of invert
  - experience of personel
  - ....

WHICH METHOD ?

- **Working Group 1.6 of DGGT**
  > Load Reduction Method

- **Stiffness Reduction Method**
  Influence of
  - **Poisson ratio**
  - **Constitutive model**

- **Correlation of α and β very difficult**
  (Baumann & Hilber 1985, Schweiger et al. 1997)

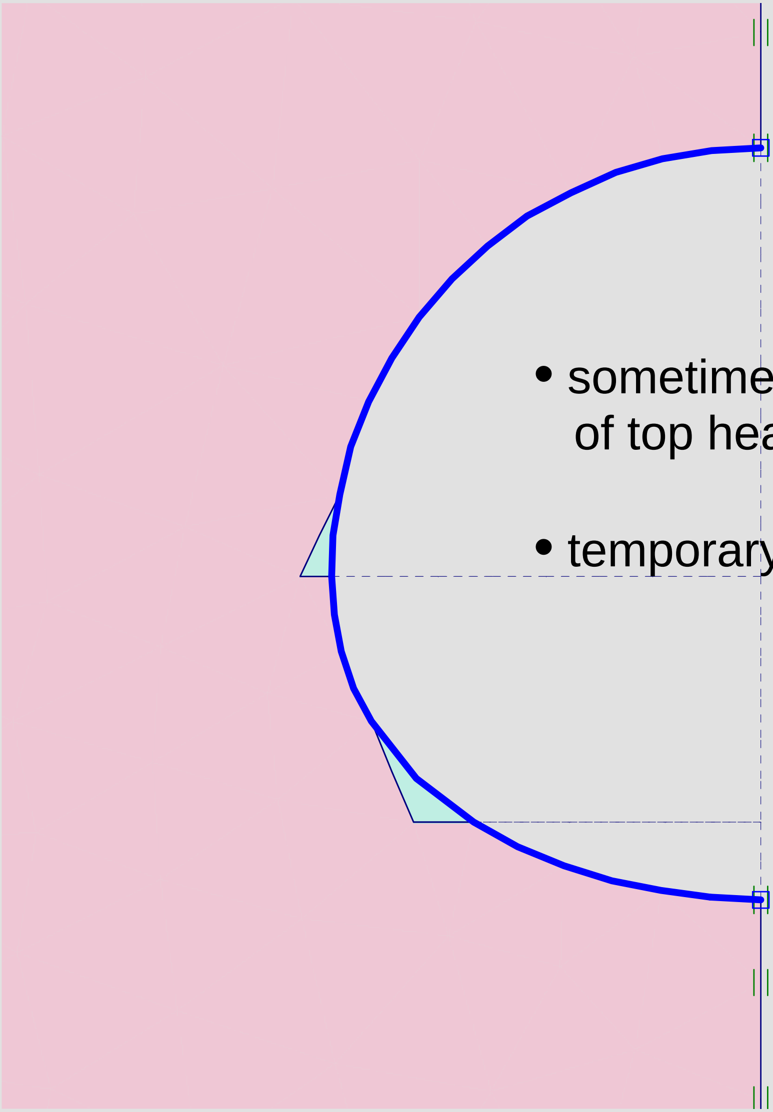
MODELLING OF SUPPORT MEASURES

- **Shotcrete**
  - **strength and stiffness highly time dependent**
  - **increase of Young's modulus for subsequent excavation steps is a practical approach**
  - **alternatively complex constitutive model can be used**

- **Rock bolts**
  - **in practice often by means of increase of cohesion**
  - **special elements of various types** (bars, beams, ..)

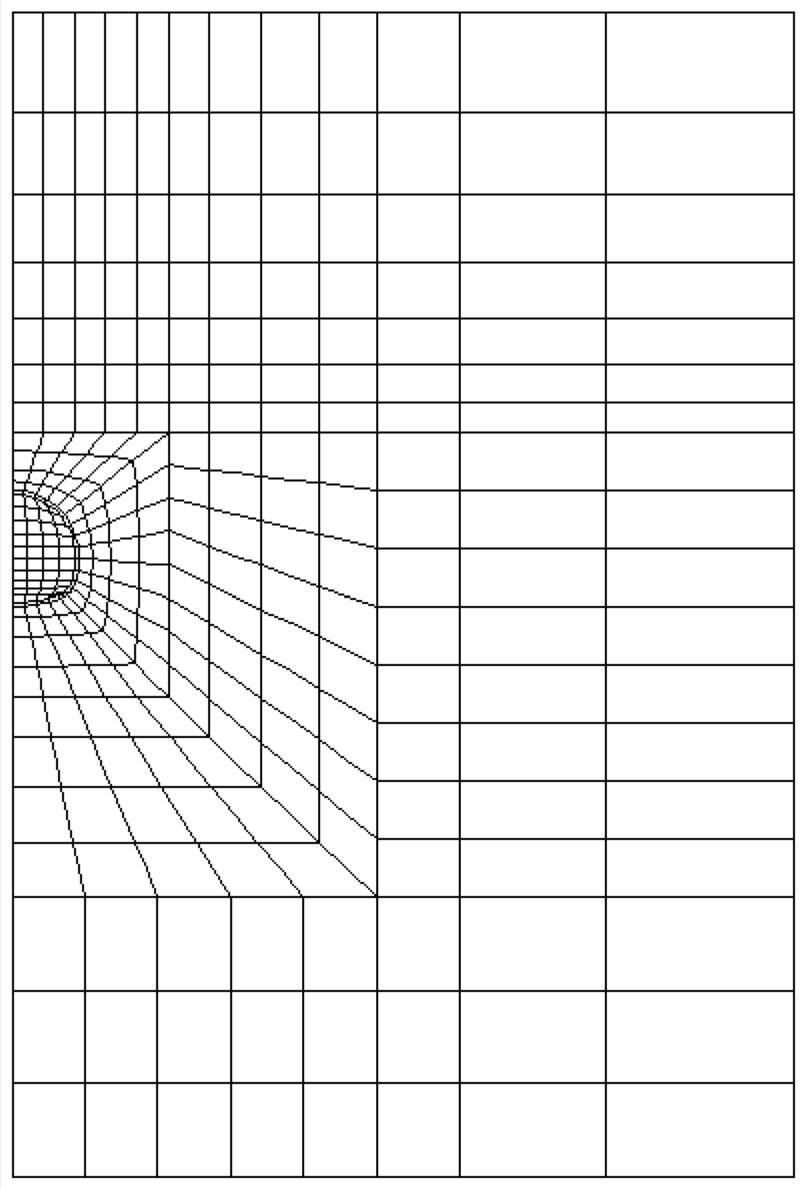
- **Final concrete lining**
  - **additional calculation without modelling of excavation sequence in detail** (subgrade reaction method)
  - **from FE-analysis assuming that shotcrete lining carries no load in the long term**

SUPPORT TOP HEADING



- sometimes not sufficient support for beam of top heading > numerical problems
- temporary invert for top heading

BOUNDARY CONDITIONS



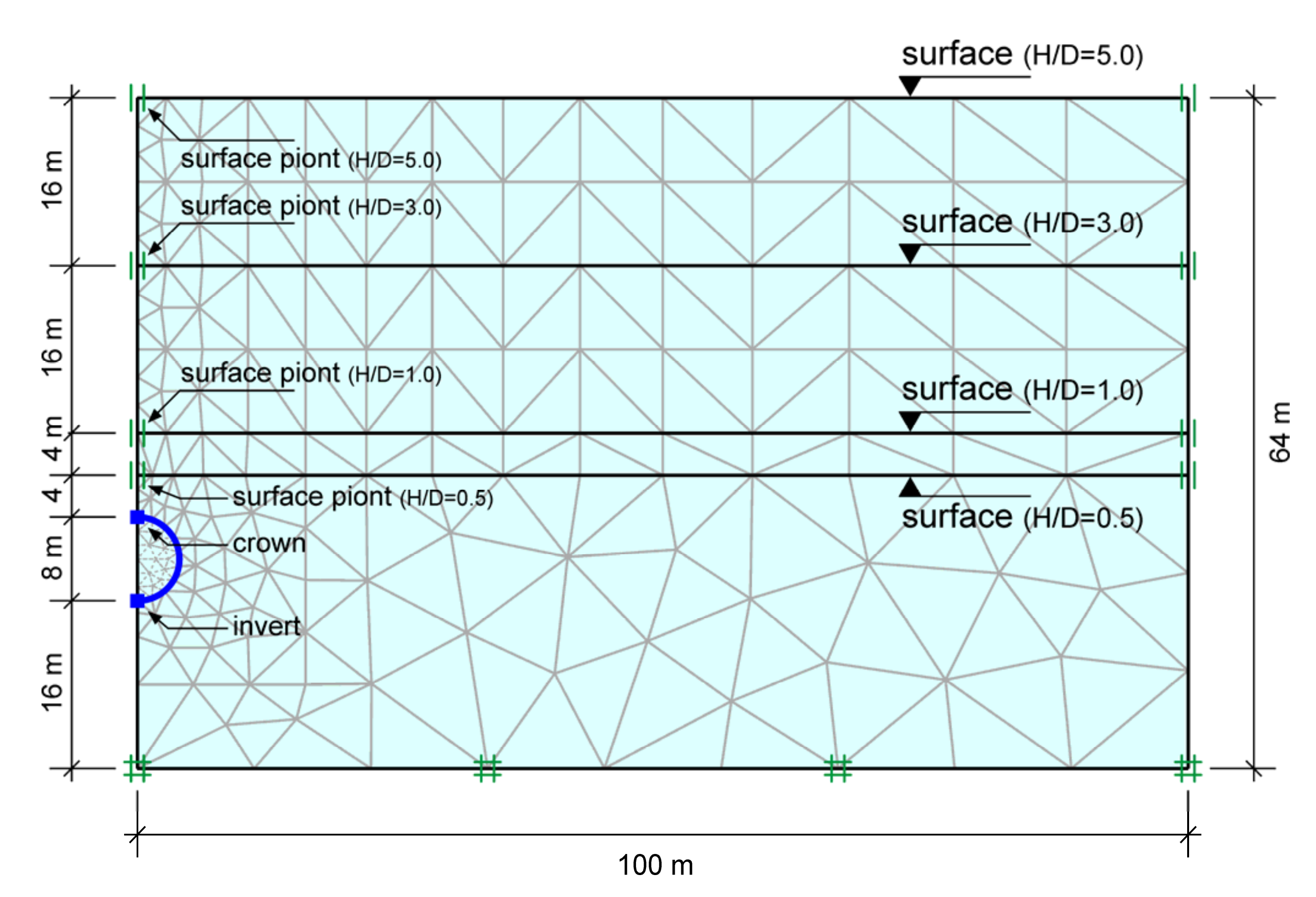
lateral: approx. 4 - 5 D

top: ground surface or approx. 3 D

bottom: 2-3 D (geology !?)

attention in rocks when joints are present !

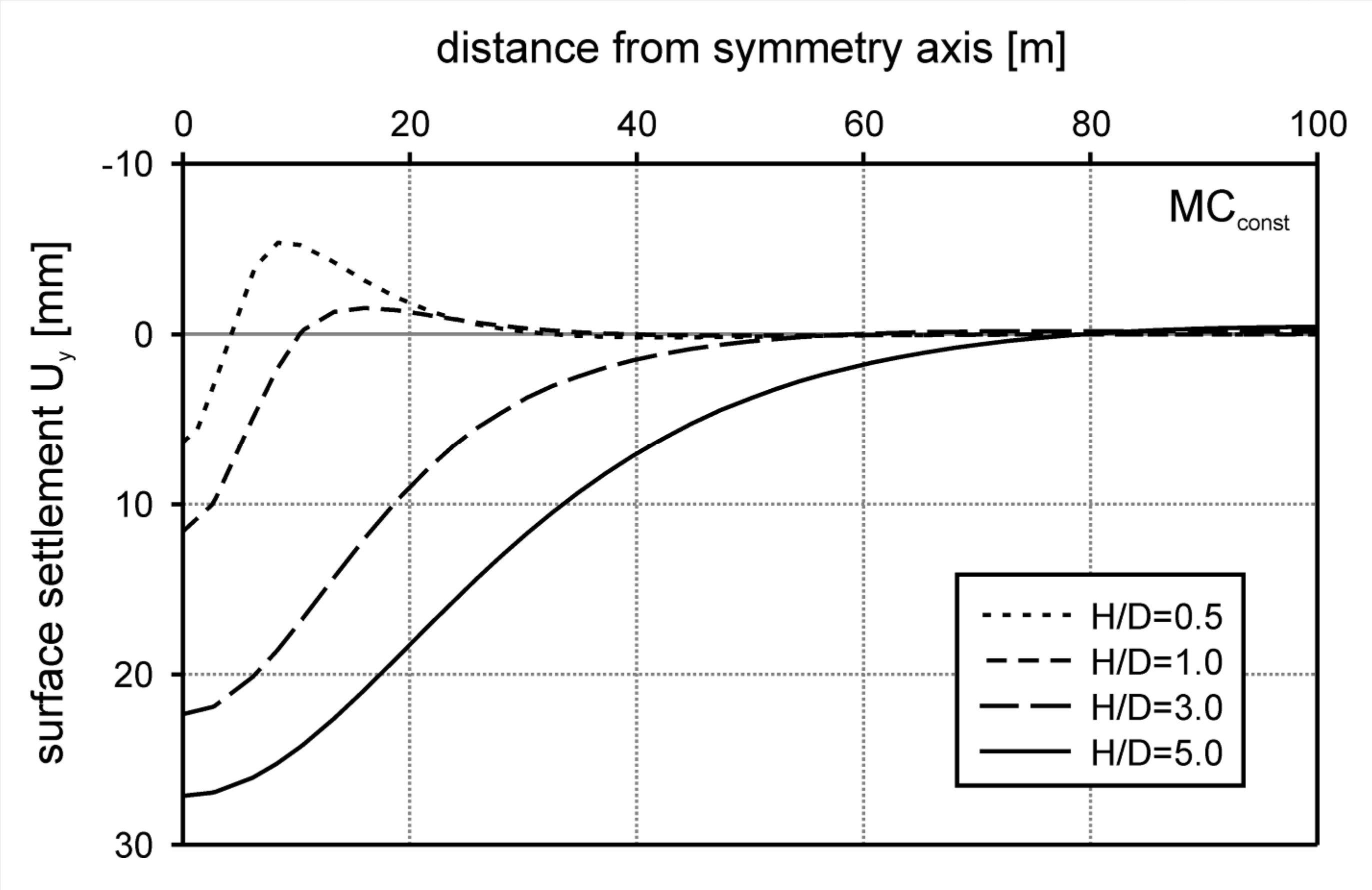
EXAMPLE - INFLUENCE OF SMALL STRAIN STIFFNESS



- Variation of overburden (H/D=0.5, 1.0, 3.0, 5.0)
- Increase of distance between tunnel and bottom boundary of the mesh to 4D
- Multilaminate Model for Soil, Mohr-Coulomb Model

SURFACE SETTLEMENTS

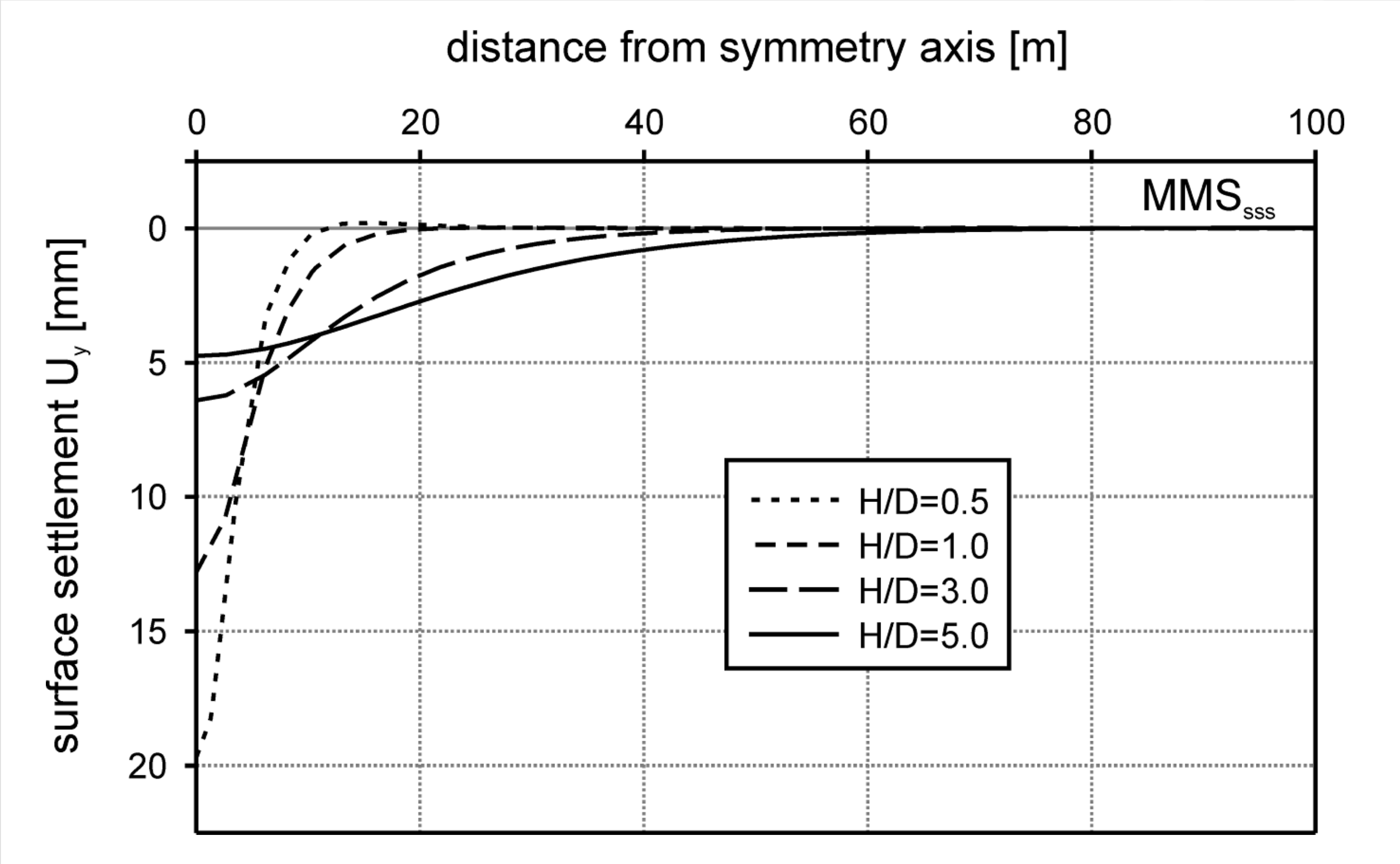
Mohr-Coulomb Model



- Variation of overburden (H/D=0.5, 1.0, 3.0, 5.0)

SURFACE SETTLEMENTS

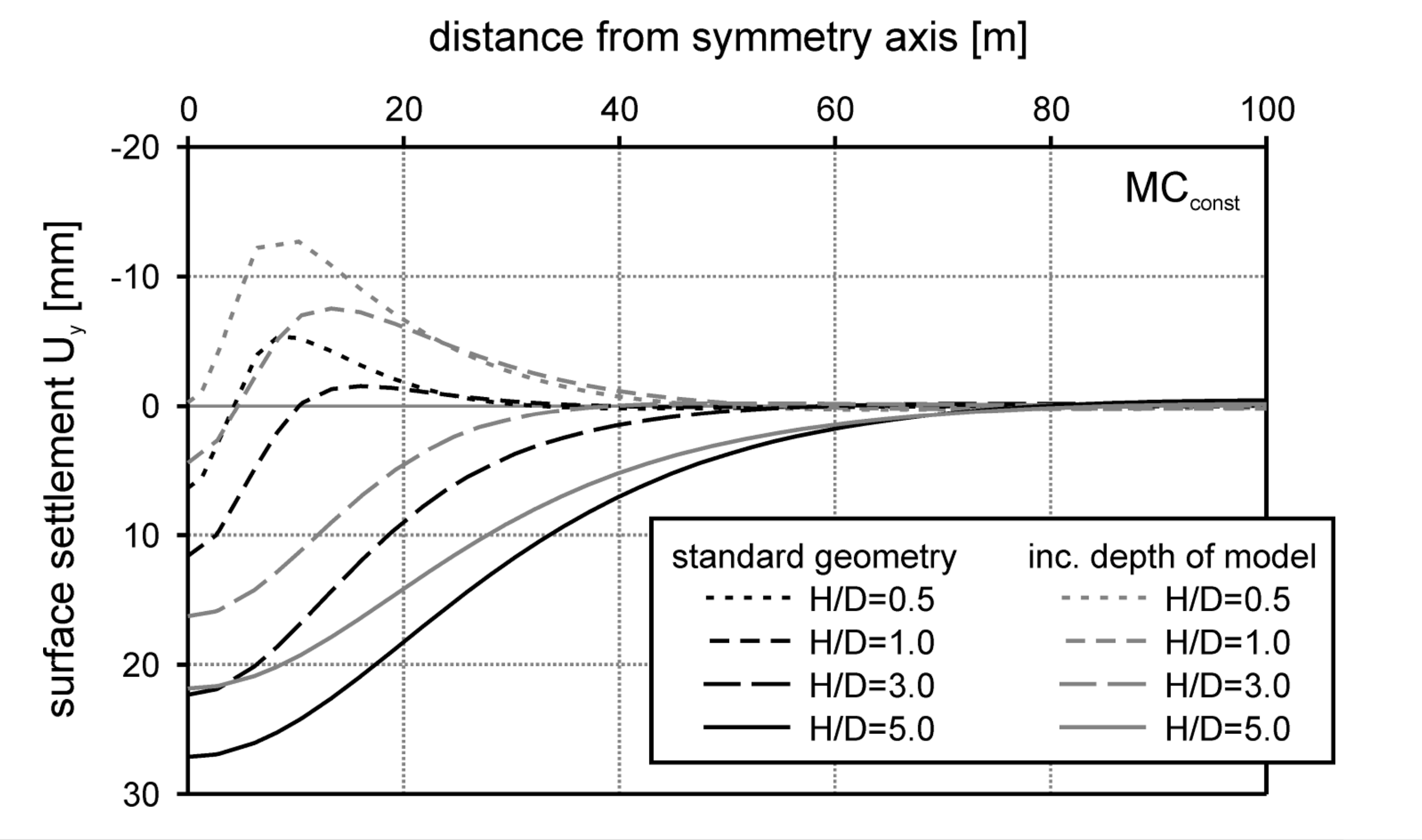
Multilaminate Model for Soil with small strain stiffness



- Variation of overburden (H/D=0.5, 1.0, 3.0, 5.0)

SURFACE SETTLEMENTS

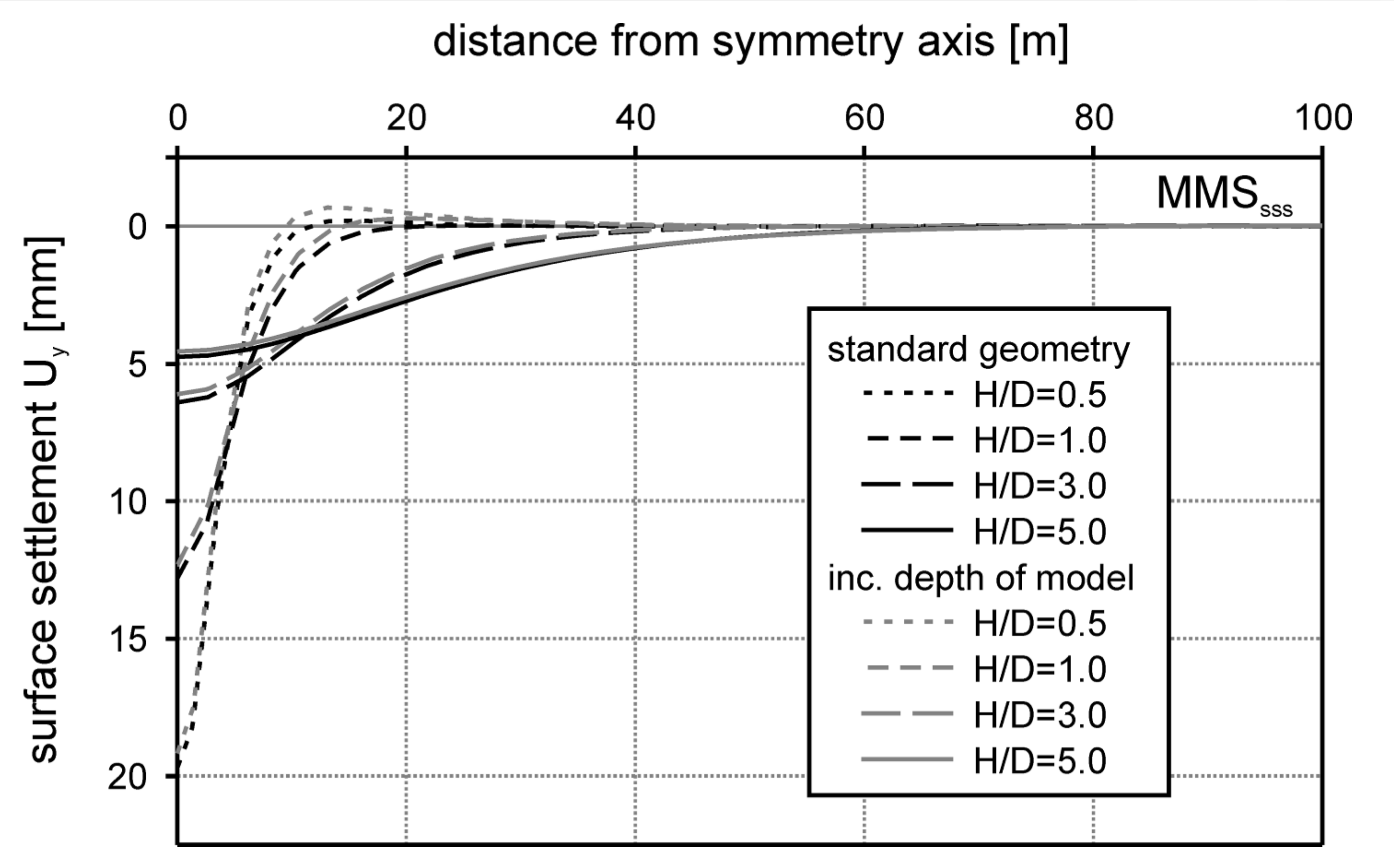
Mohr-Coulomb Model



- Increase of distance between tunnel and bottom boundary of the mesh

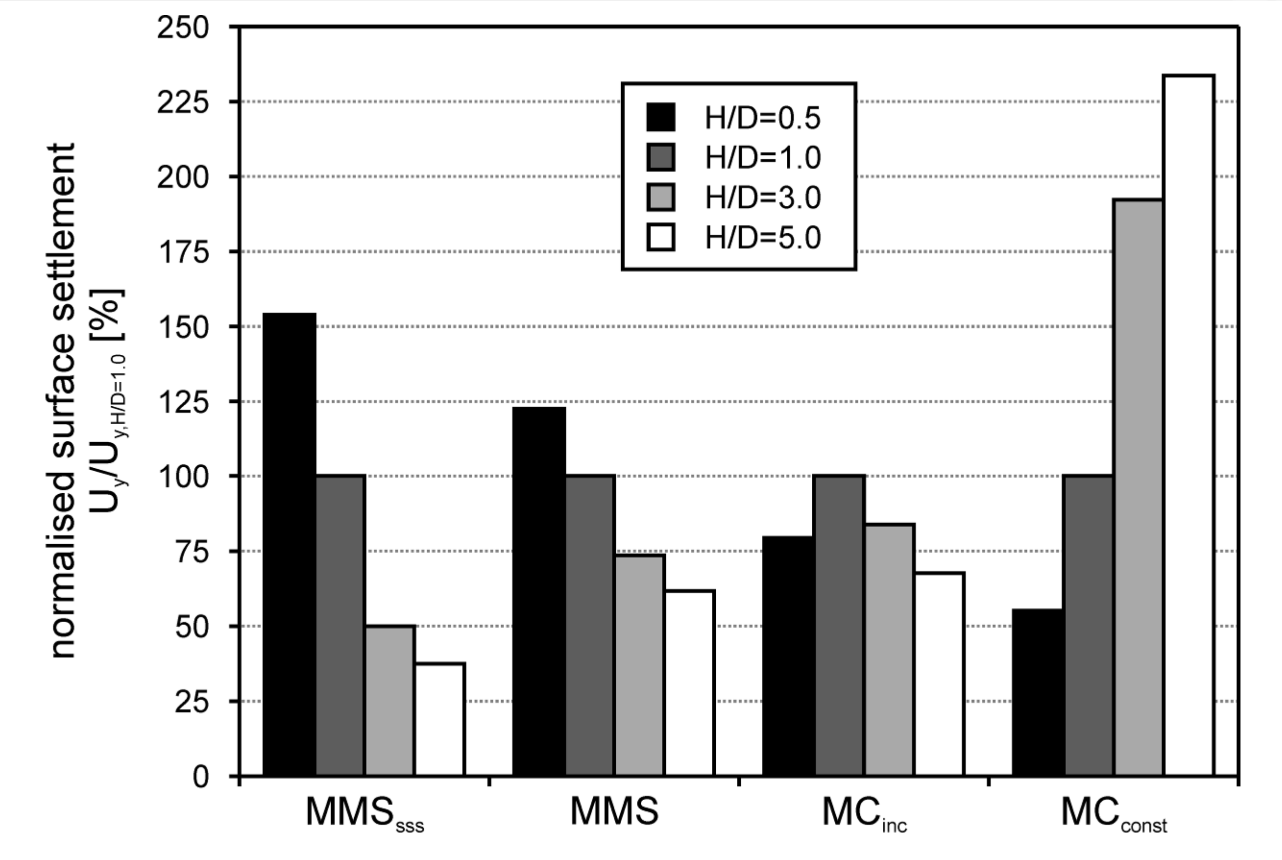
SURFACE SETTLEMENTS

Multilaminate Model for Soil with small strain stiffness

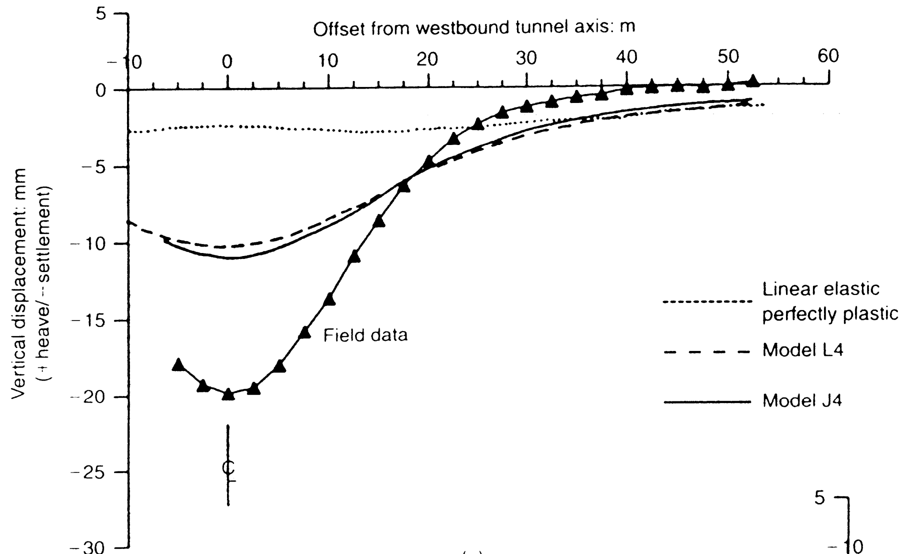


- Increase of distance between tunnel and bottom boundary of the mesh

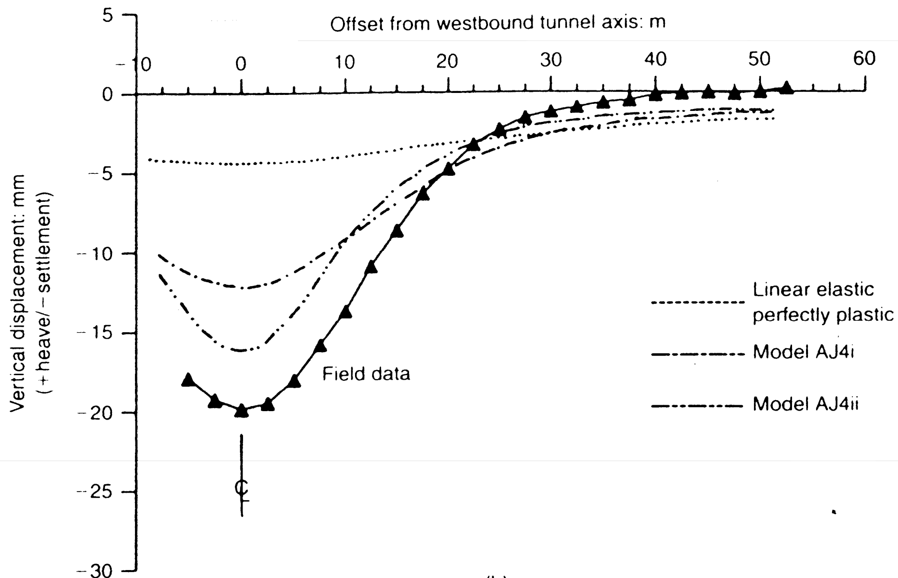
COMPARISON OF NORMALISED SURFACE SETTLEMENTS



INFLUENCE OF SMALL STRAIN STIFFNESS



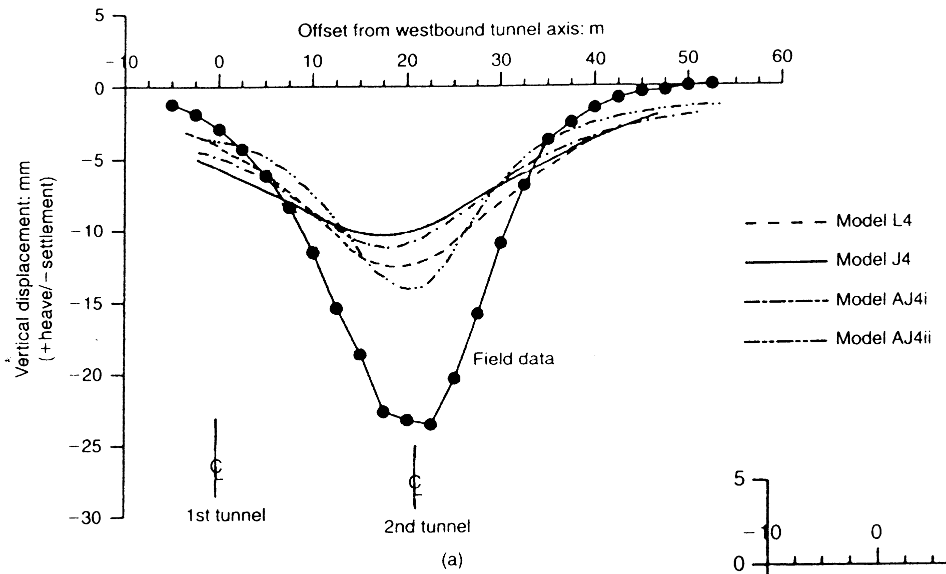
(a)

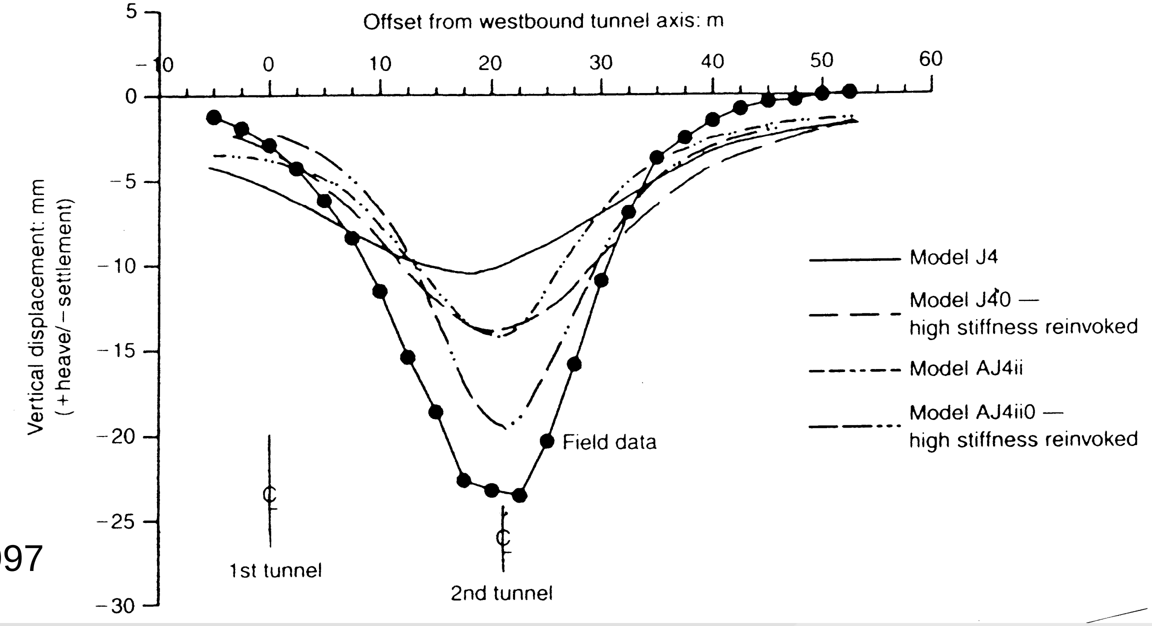


(b)

from Addenbrooke, Potts & Puzrin 1997

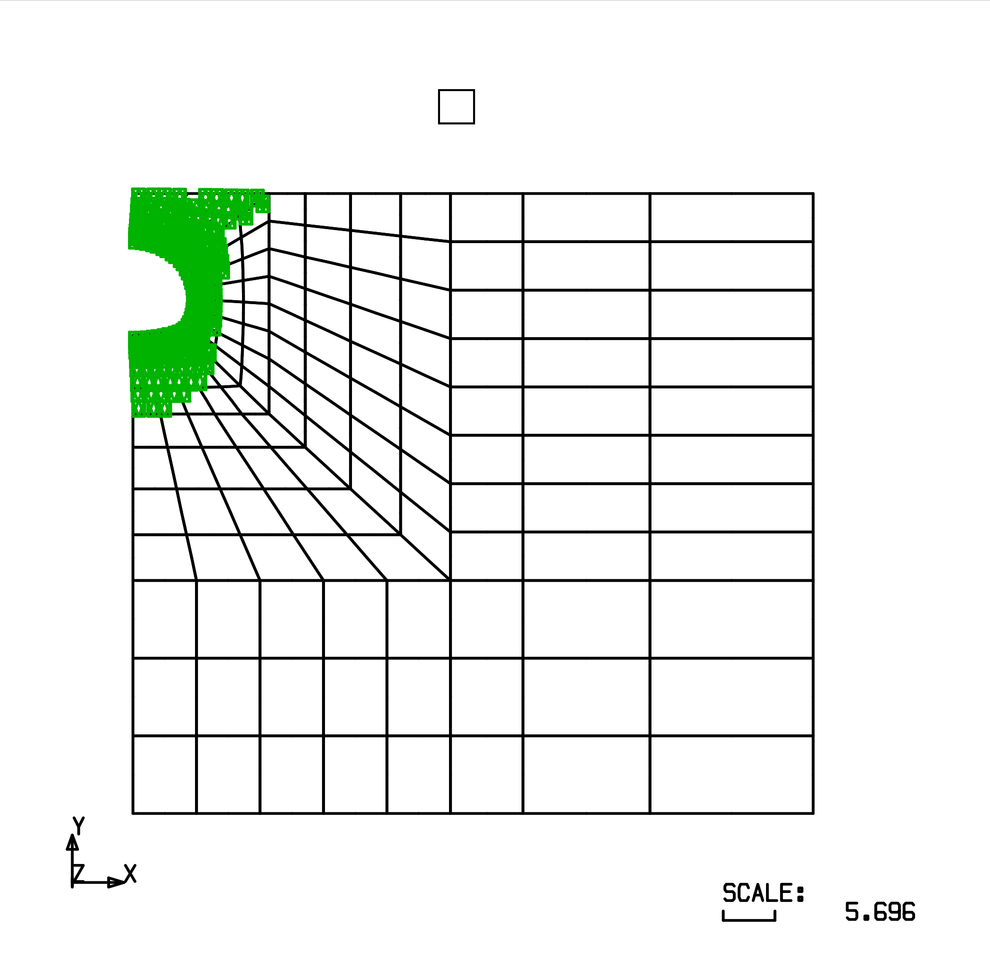
INFLUENCE OF SMALL STRAIN STIFFNESS



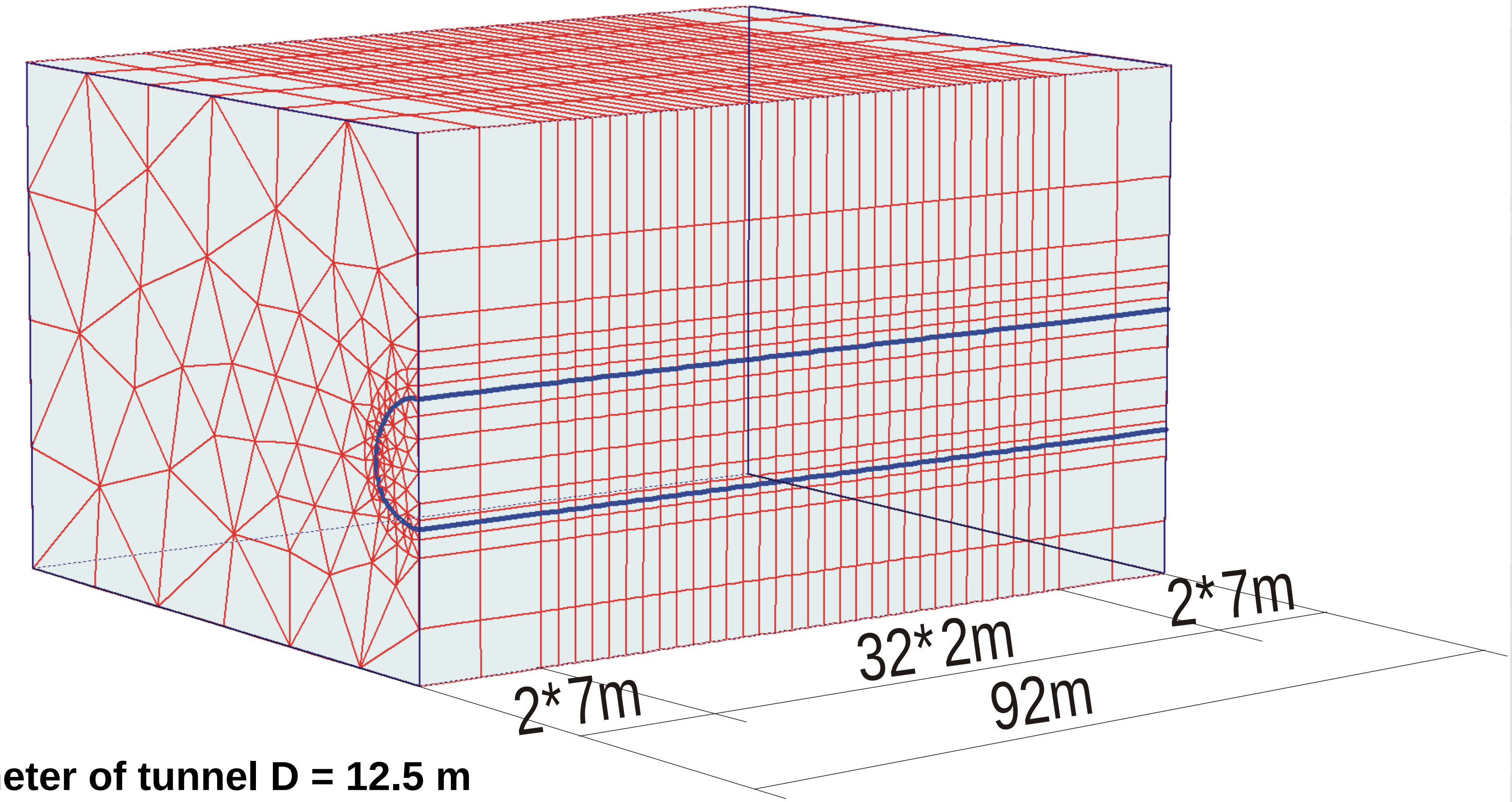


from Addenbrooke, Potts & Puzrin 1997

SMALL STRAIN REGION



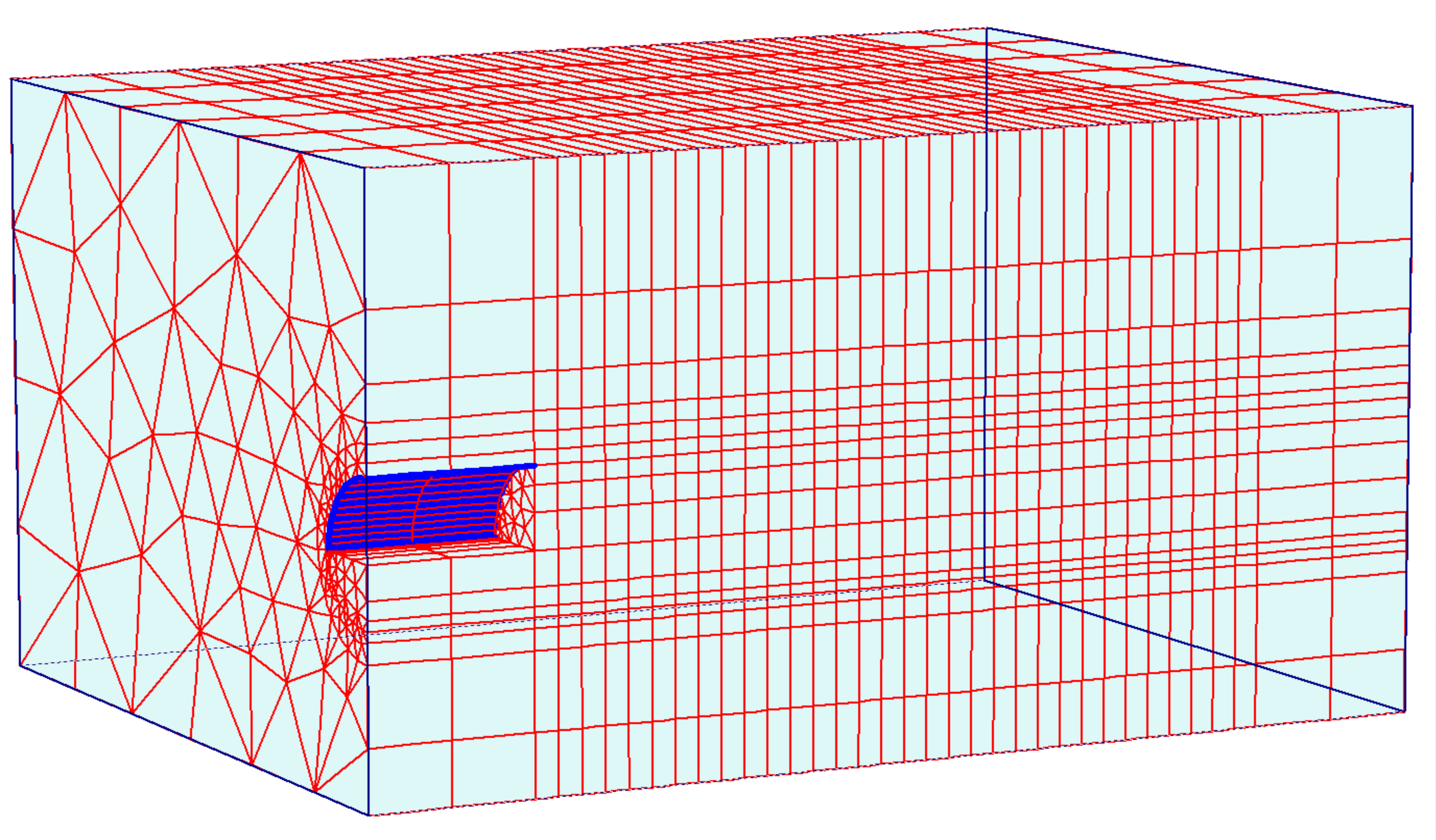
3D MODEL



diameter of tunnel D = 12.5 m

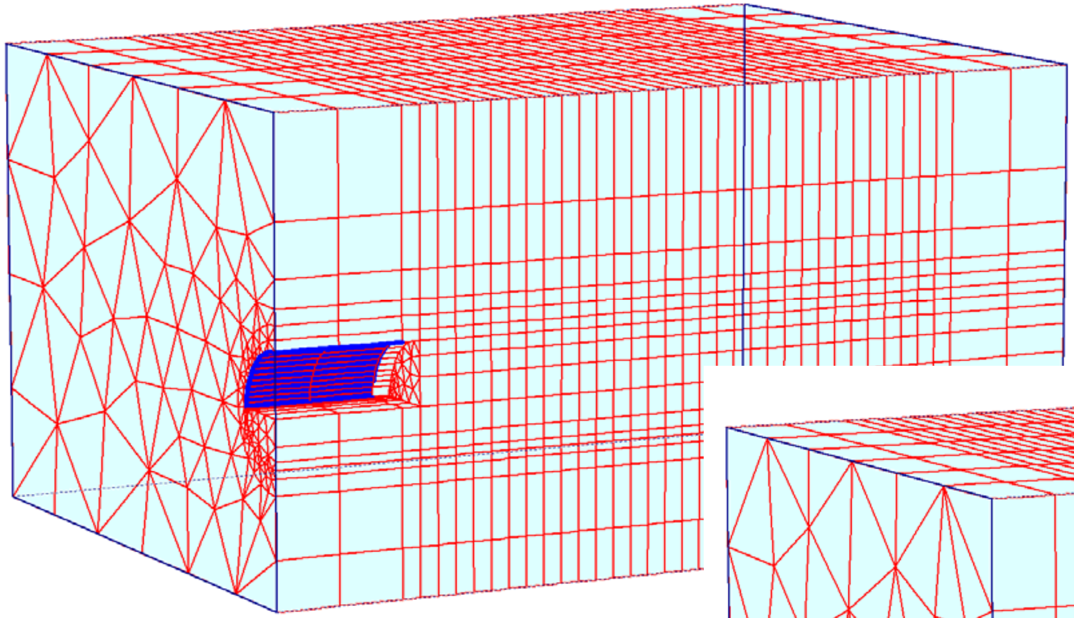
still influence of boundary !

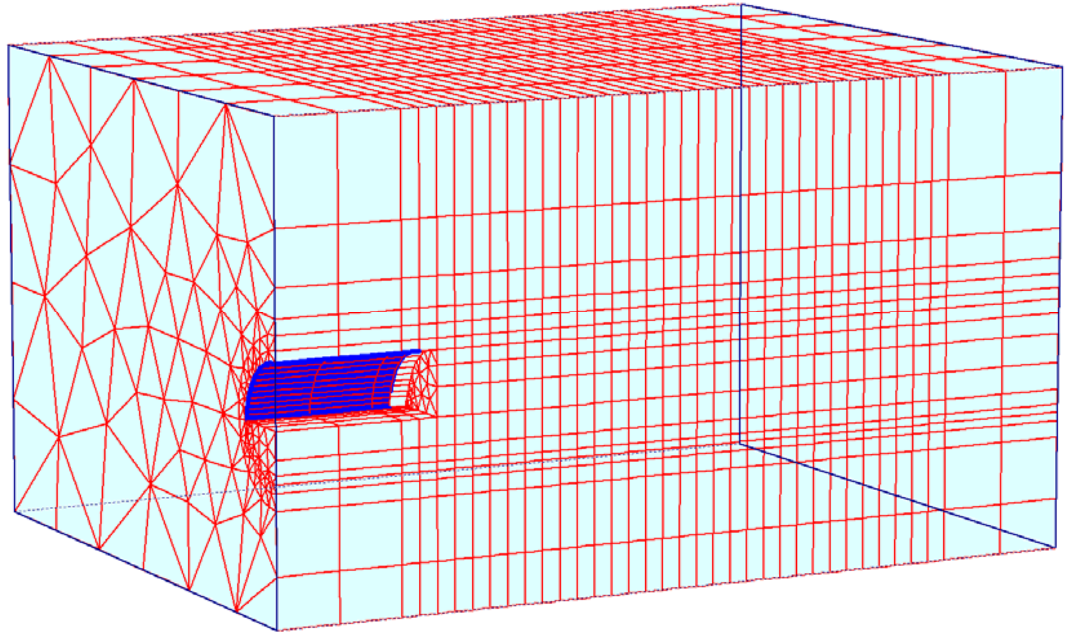
START EXCAVATION TOP HEADING



EXCAVATION TOP HEADING

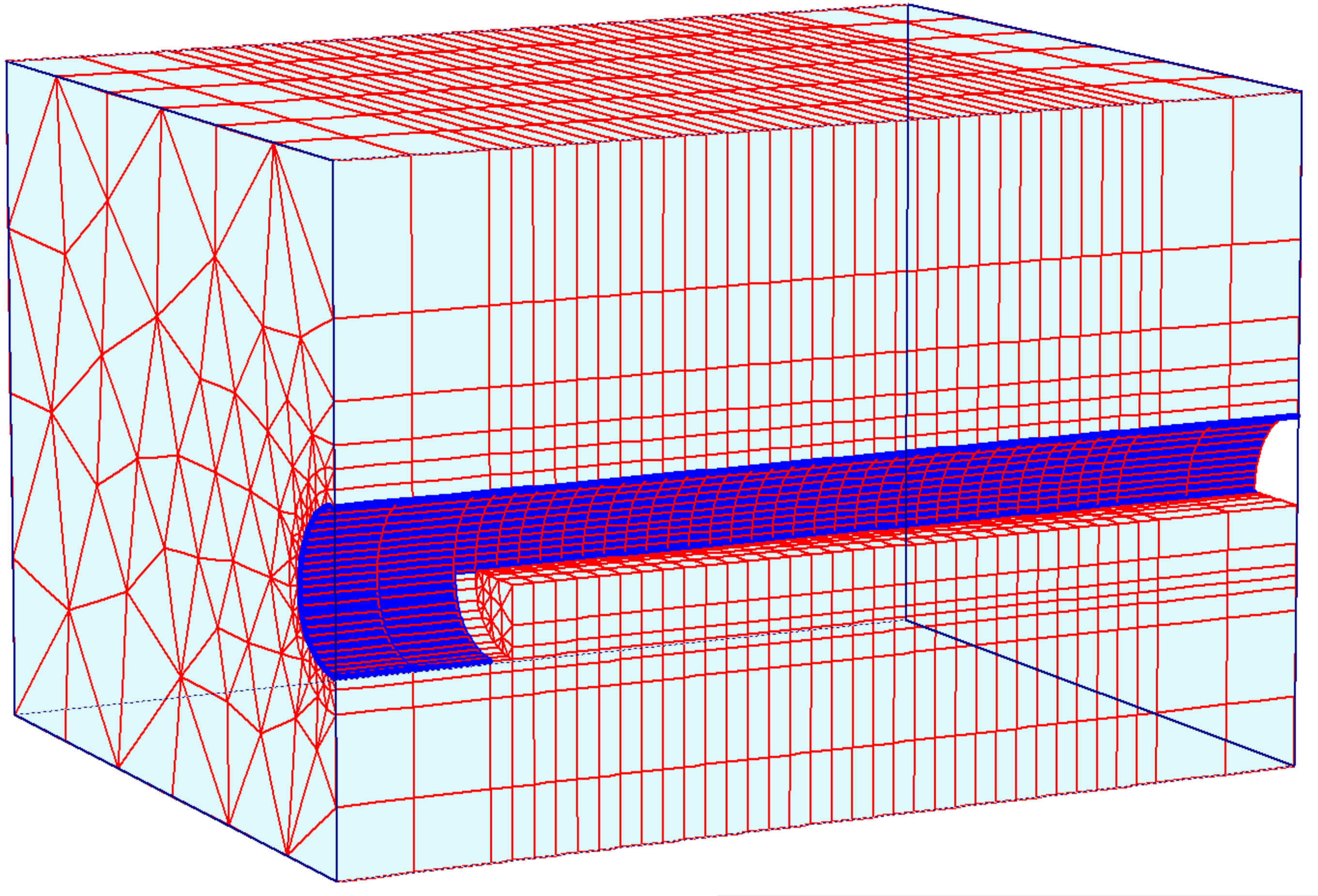
1. round top heading





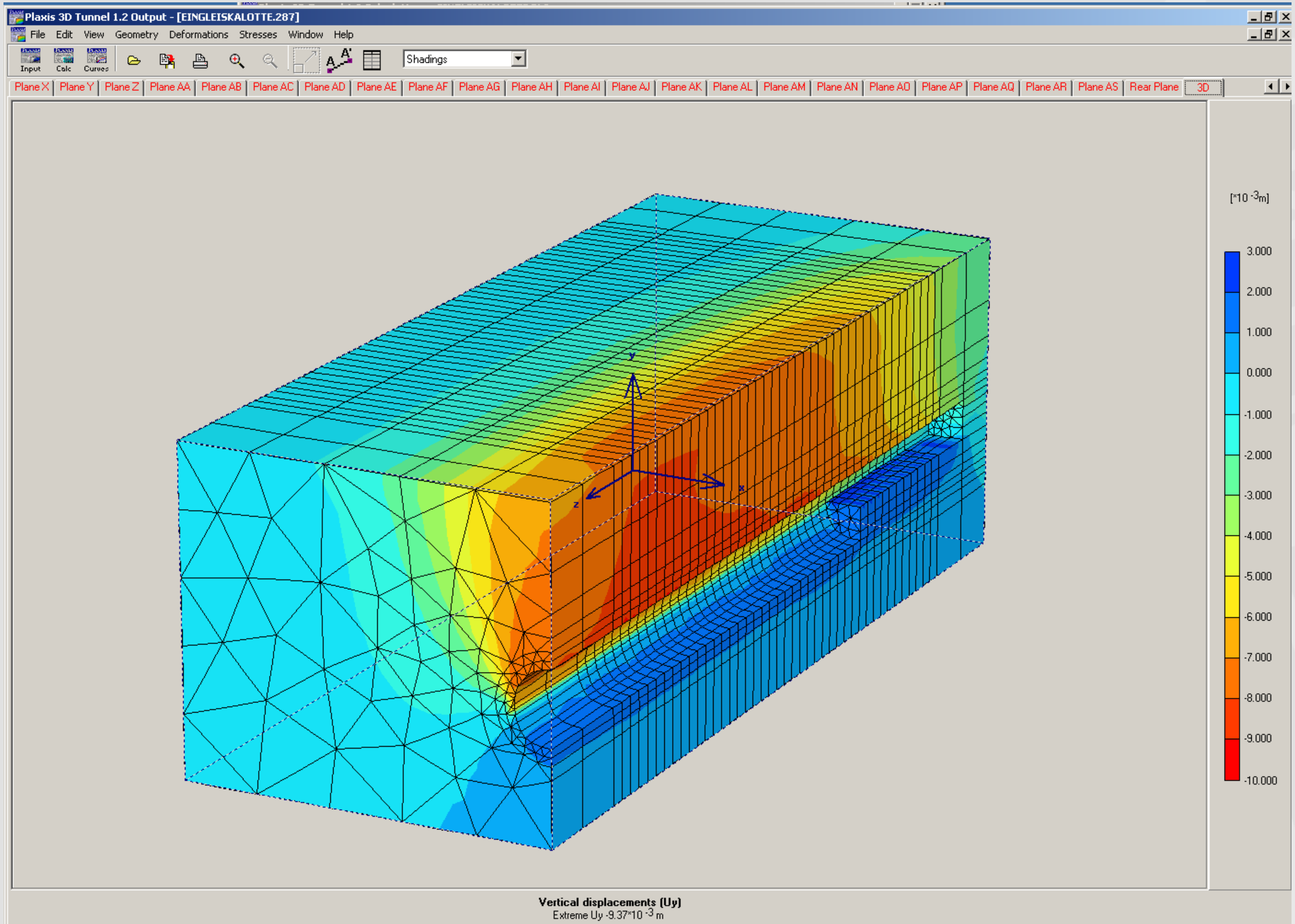
shotcrete in previous section
2. round top heading

EXCAVATION TOP HEADING

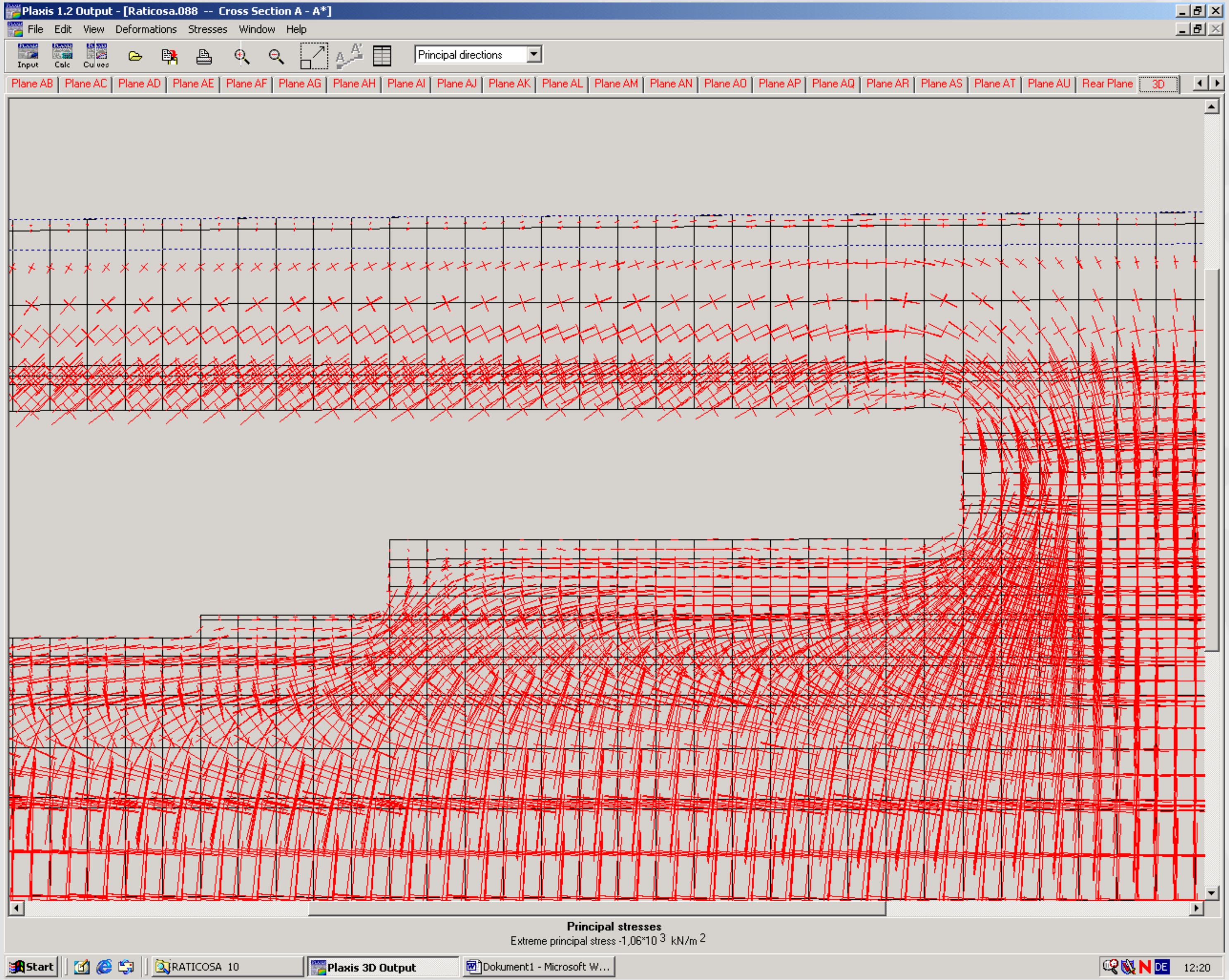


example top heading excavation well ahead of bench

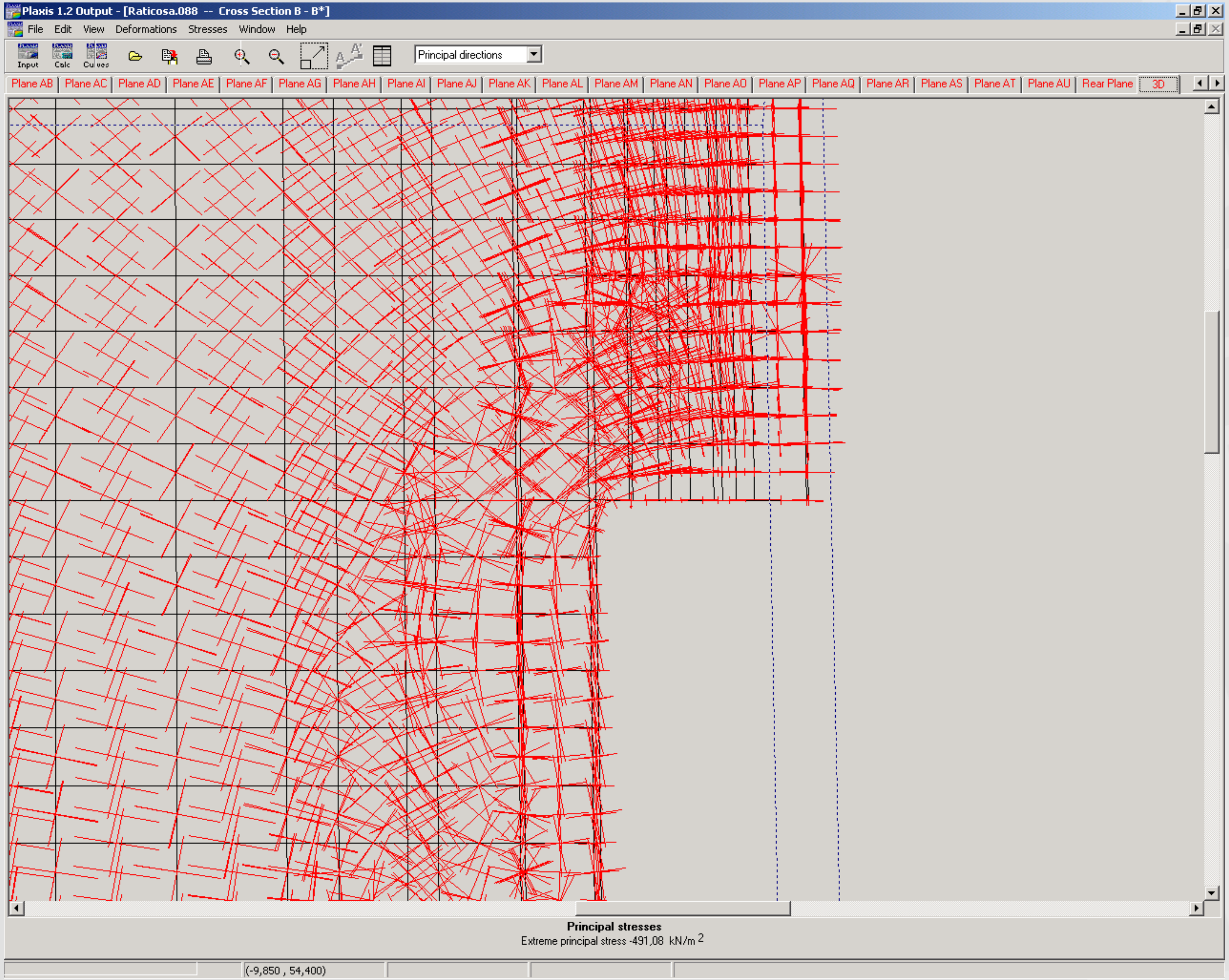
RESULTS 3D MODEL



3D MODEL - VERTICAL ARCHING

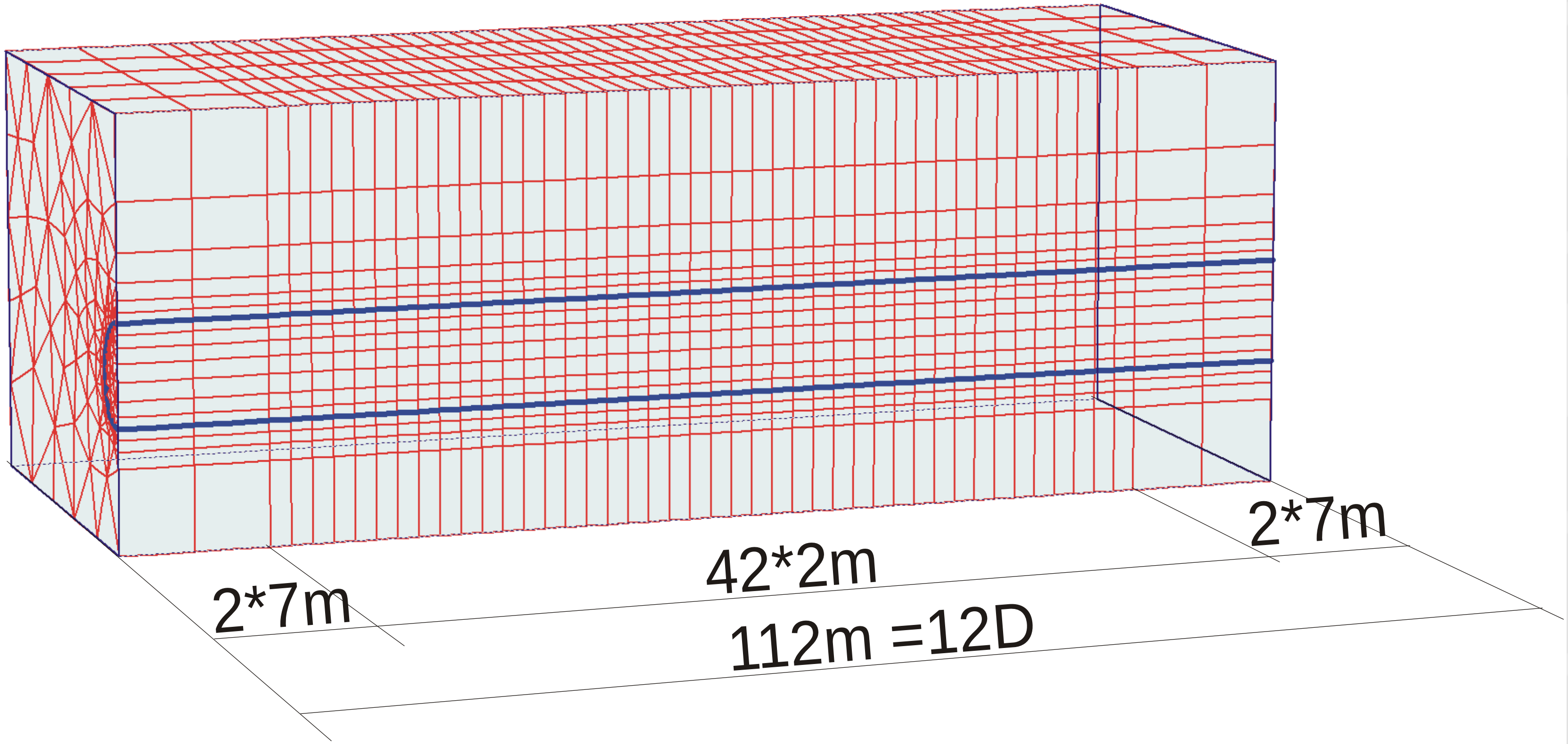


3D MODEL - HORIZONTAL ARCHING



IMPROVED 3D MODEL

diameter of tunnel D = 9 m



FACE STABILITY

Pictures: IC-CONSULENTEN, WIEN - SALZBURG

SAFETY FACTOR WITH FEM

Definition of safety factor obtained by FEM (available = *unfactored* value)

$$\eta_{fe} = \frac{\tan\varphi_{available}}{\tan\varphi_{failure}} = \frac{c_{available}}{c_{failure}}$$

Basically 2 possibilities to obtain factor of safety:

A) **Calculation with unfactored parameters (yields deformations for service state) > automatic reduction of strength parameters of soil until equilibrium is no longer achieved in numerical analysis** (some FE-codes do this automatically > φ/c-reduction technique)

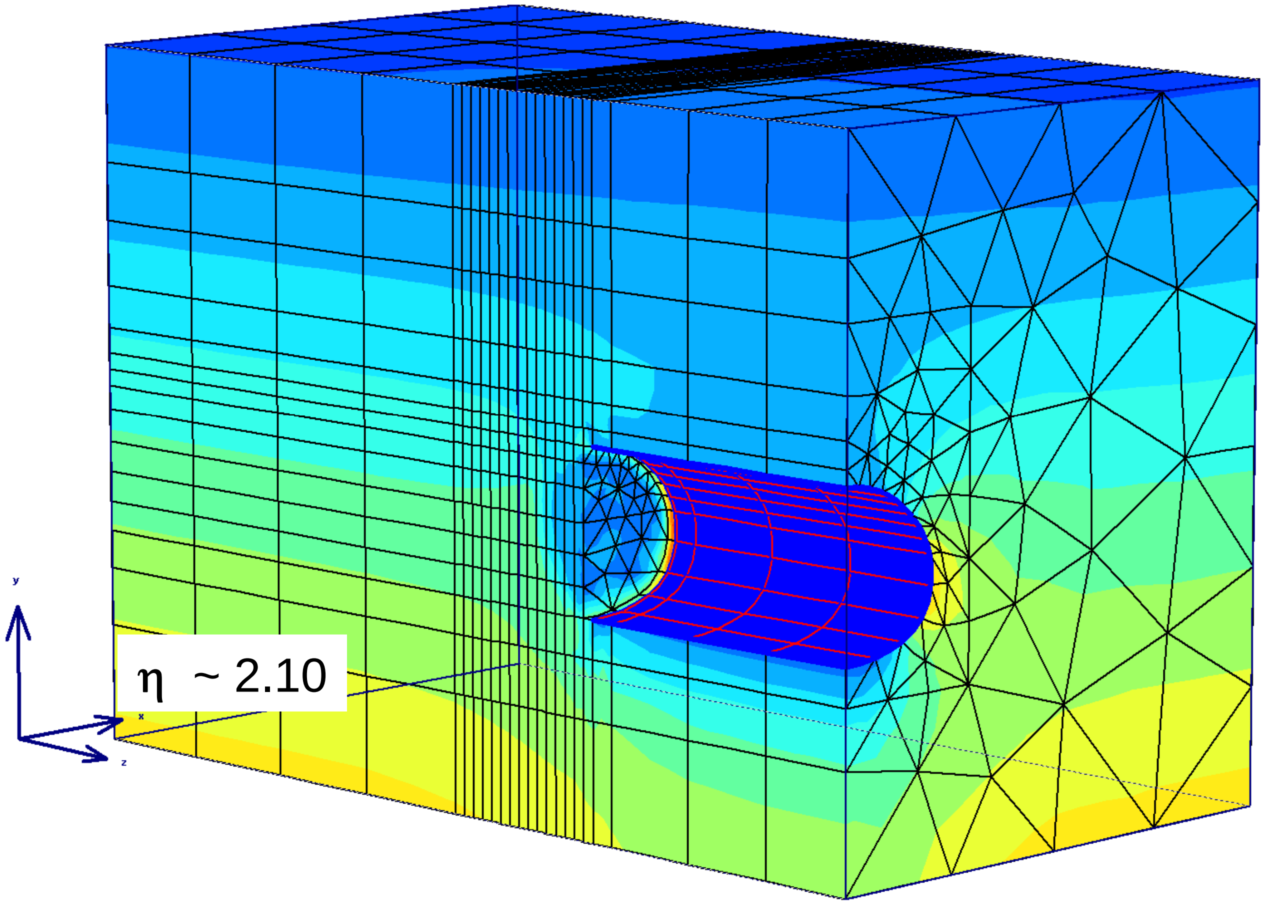
B) **Calculation with factored parameters > perform *new* calculation with different factors until equilibrium is no longer achieved in numerical analysis** (some codes do this automatically)

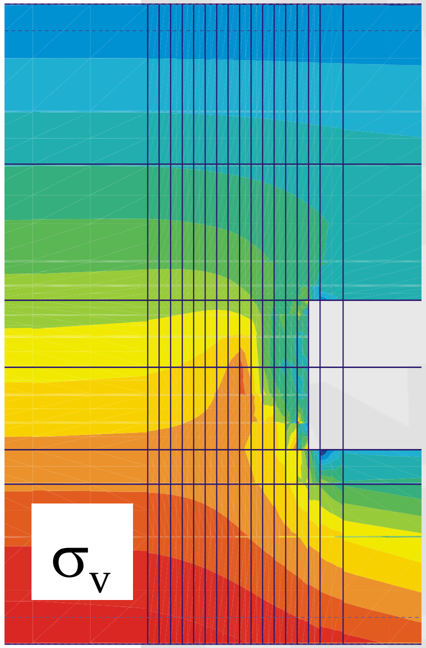
(corresponds to concept of partial factors of safety)

see also: e.g. Griffiths (1980), Naylor (1981), Brinkgreve & Bakker (1991), Matsui & San (1992)

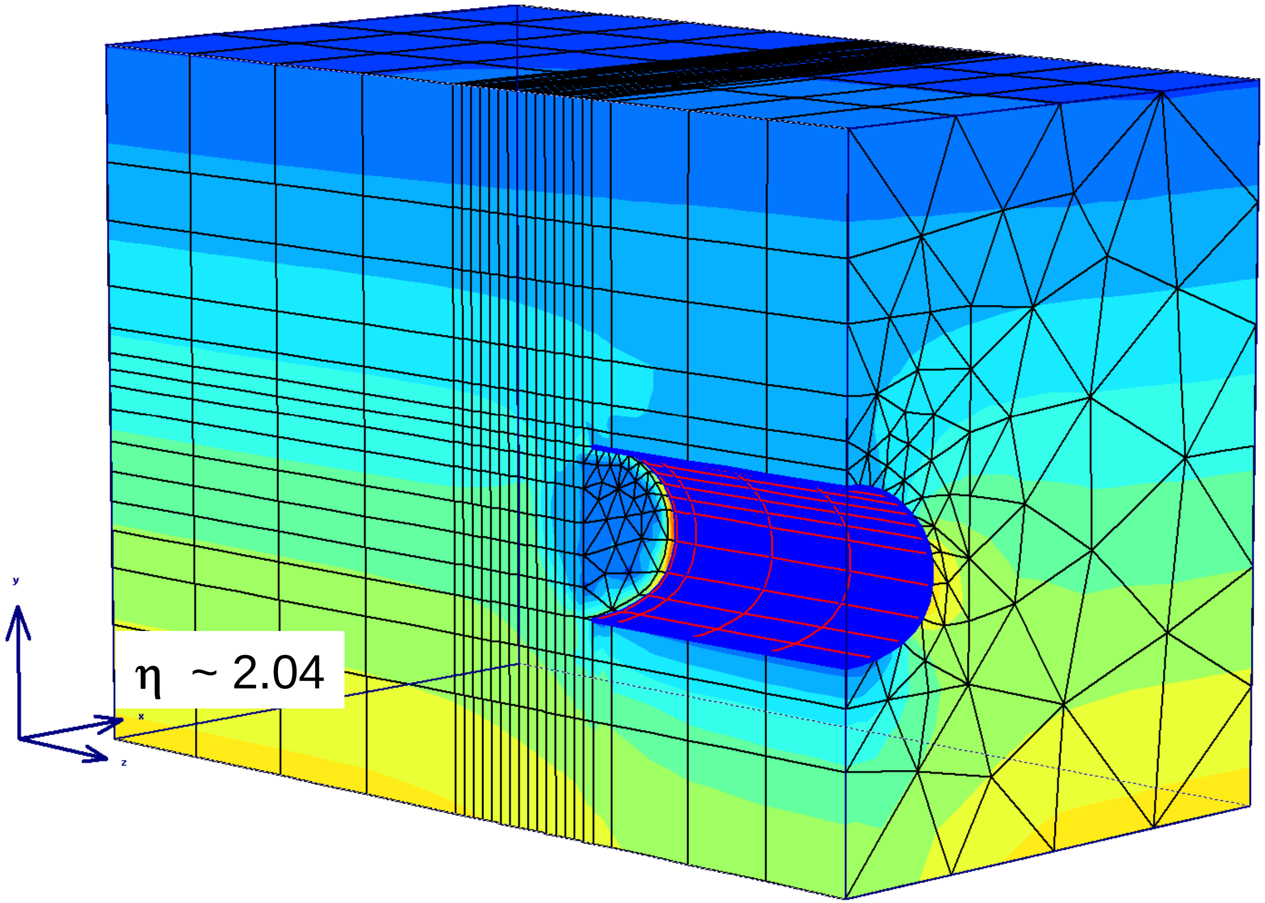
3D MODELLING - FACE STABILITY

plotted: mean normal stress $(\sigma_1+\sigma_2+\sigma_3)/3$





3D MODELLING - FACE STABILITY



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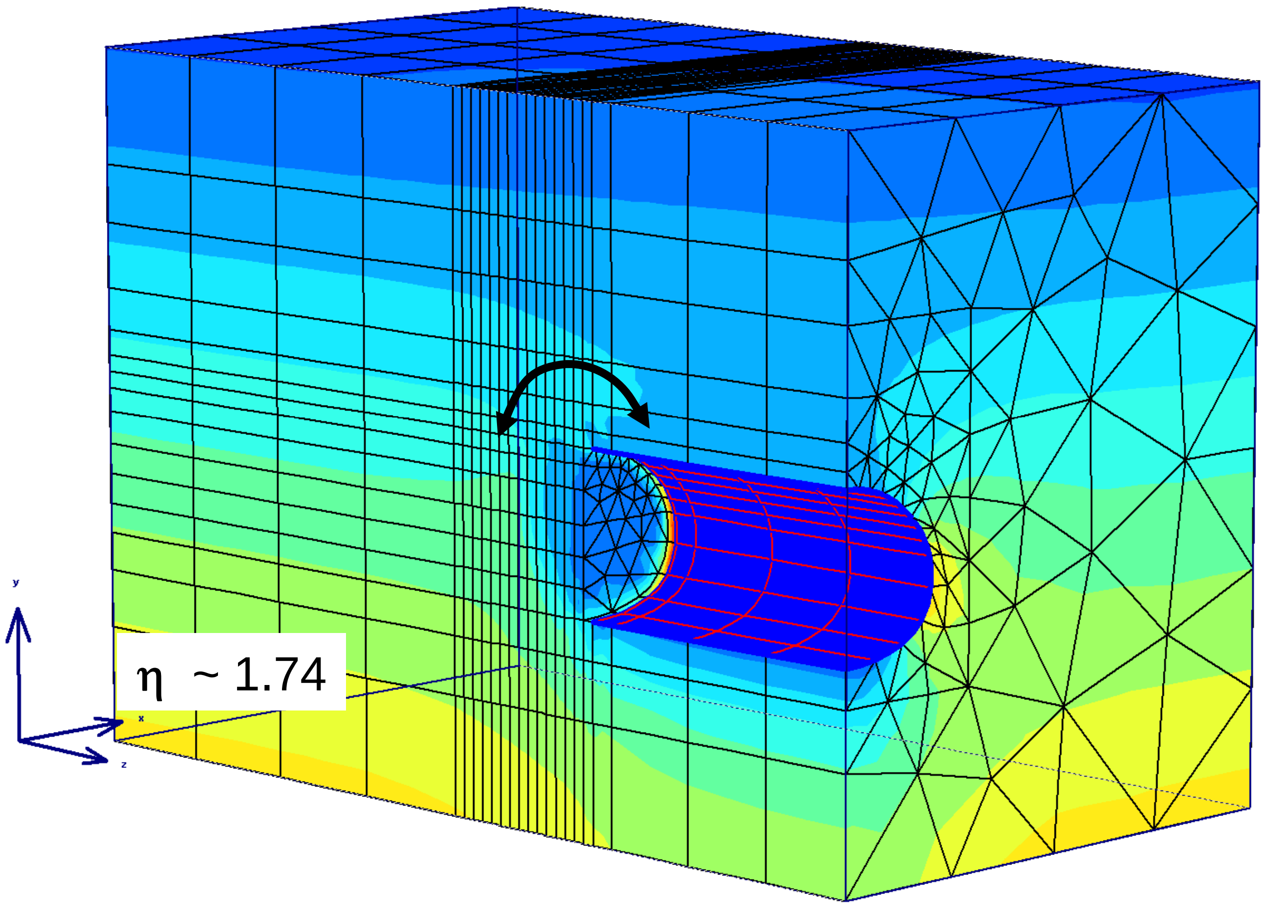

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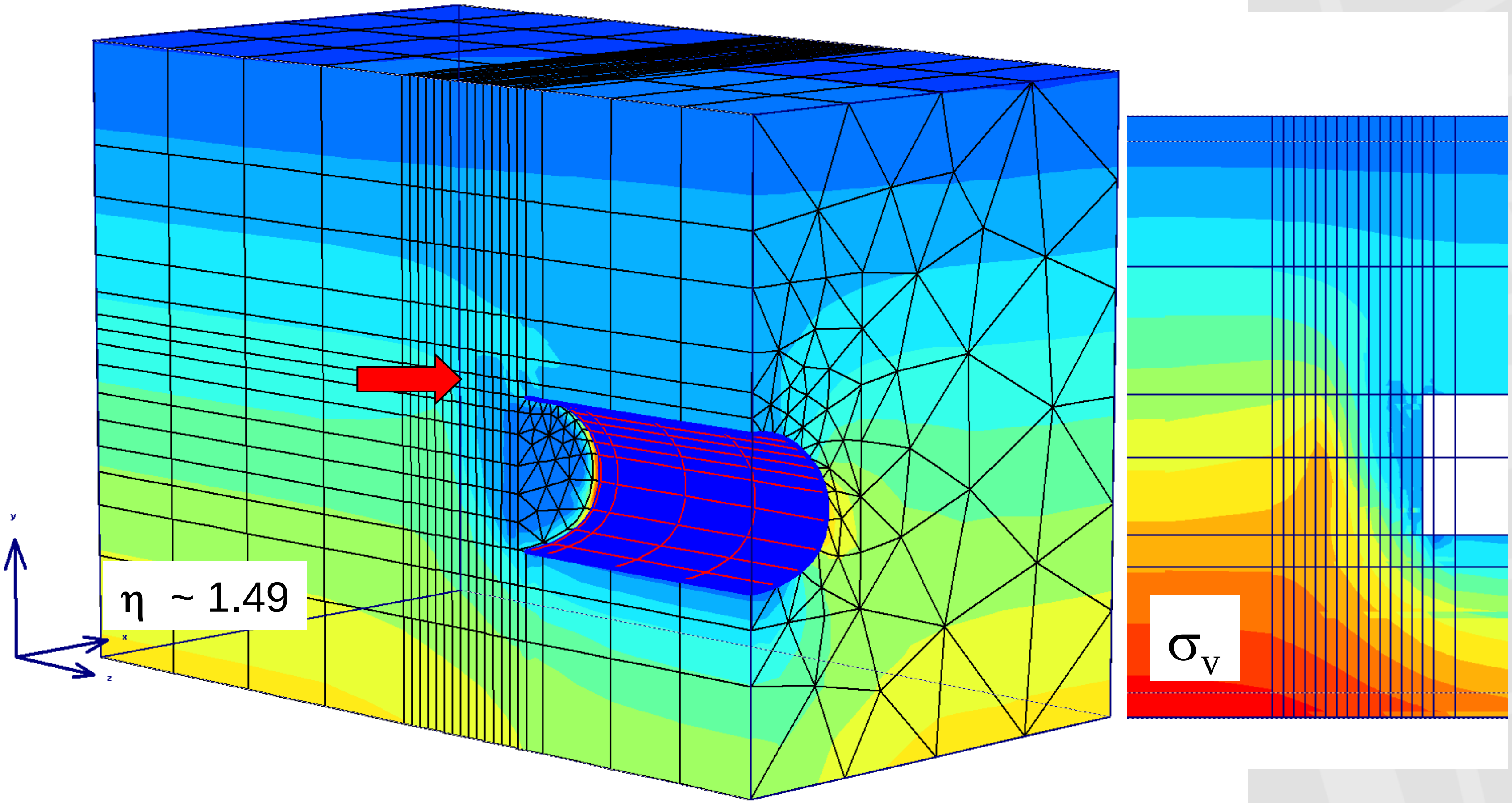

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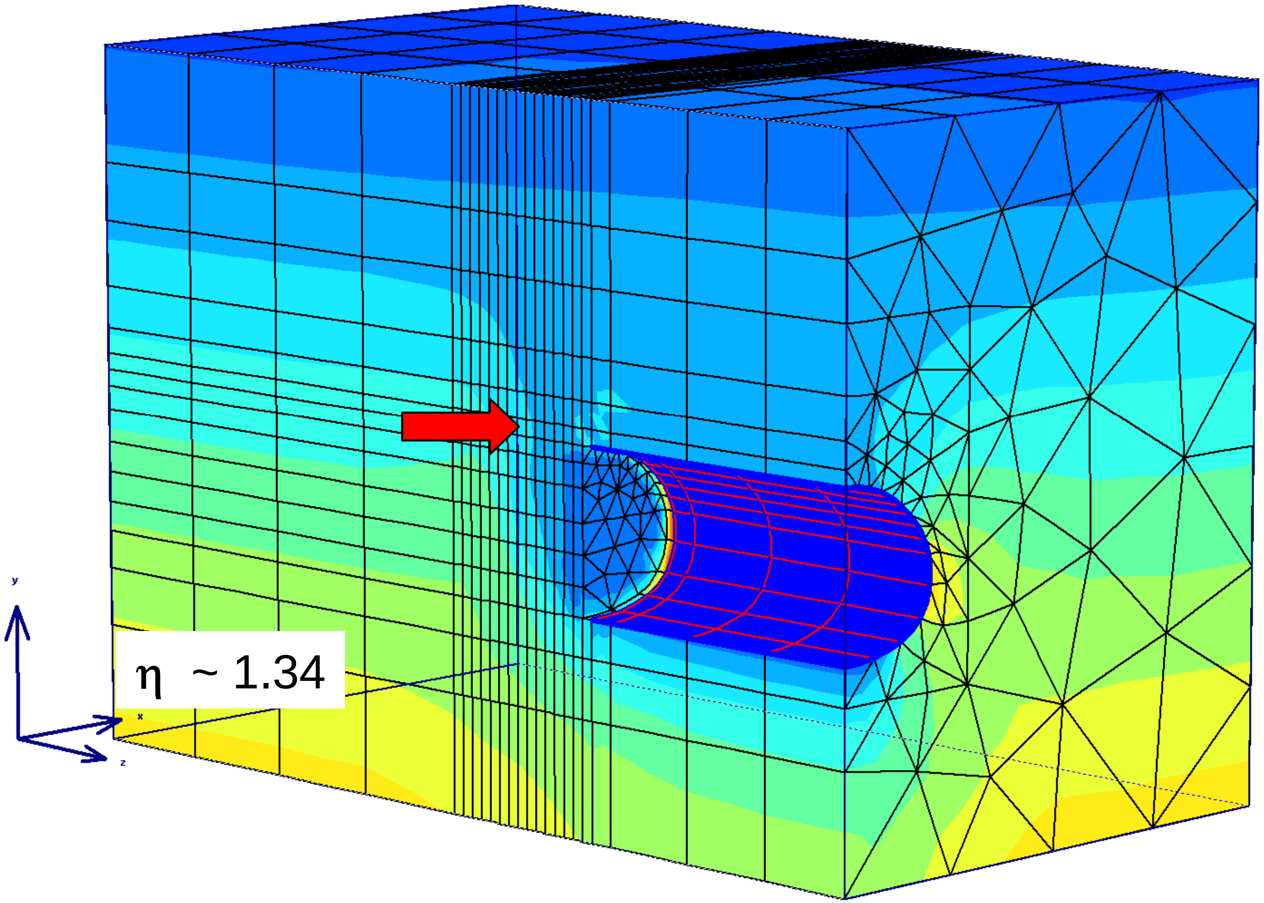

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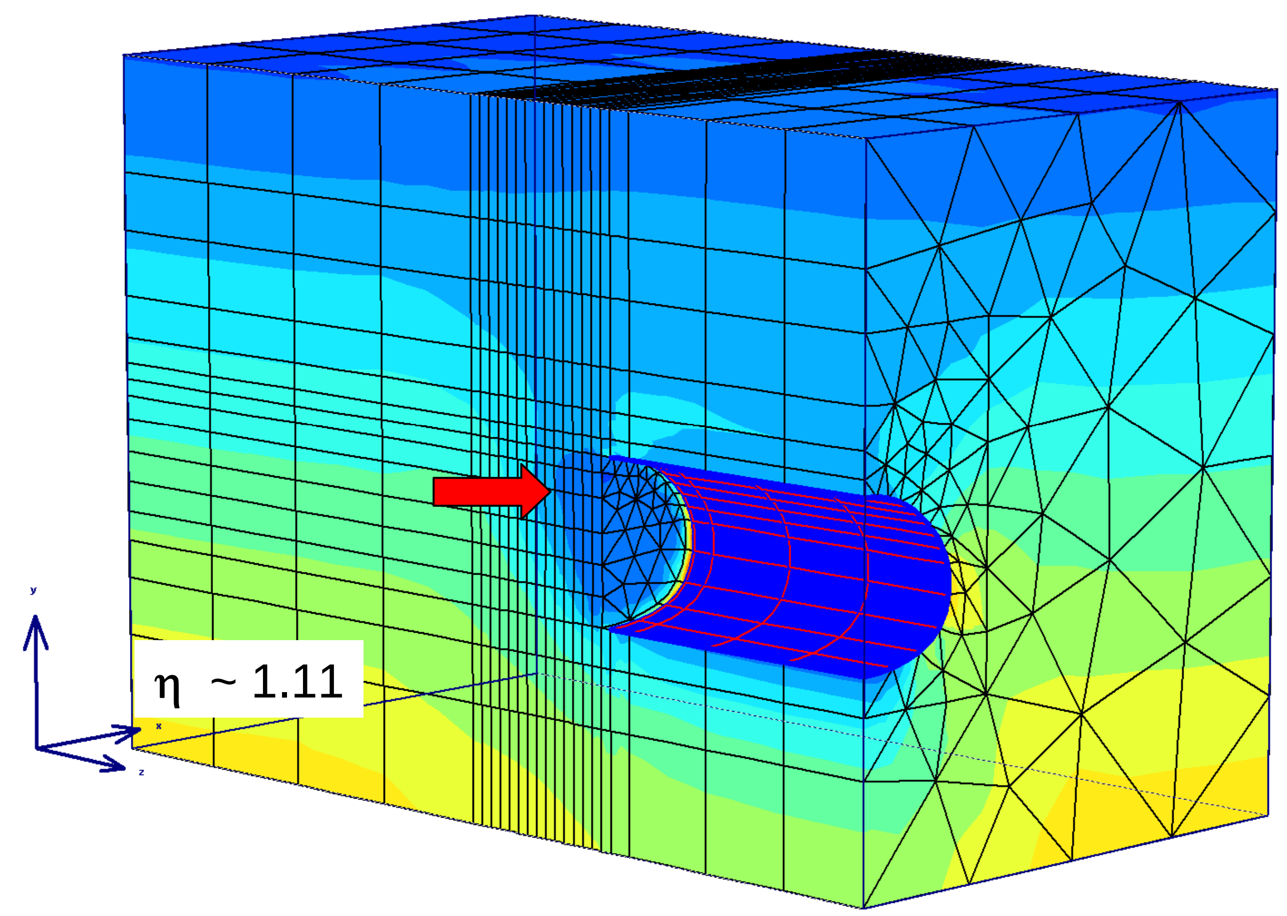

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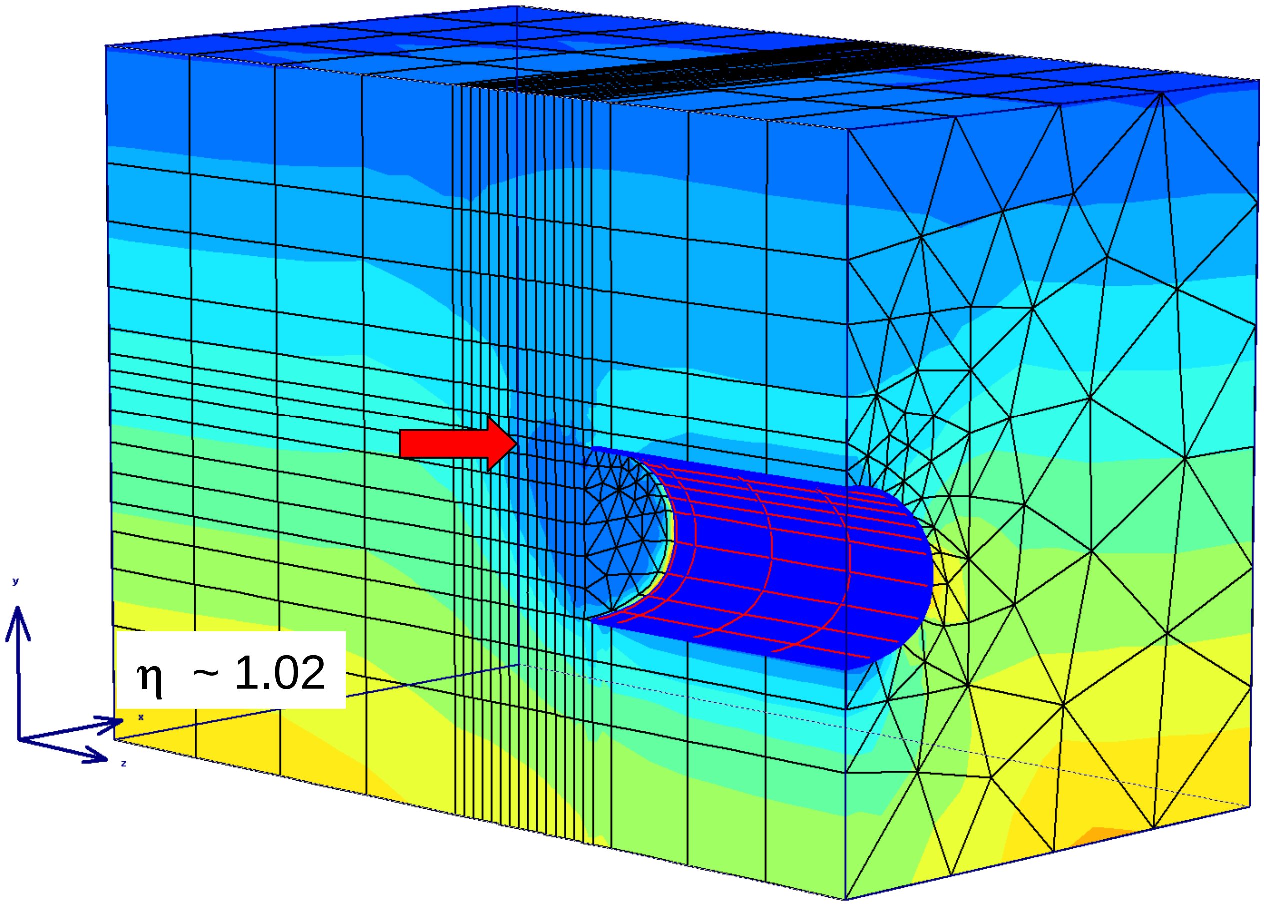

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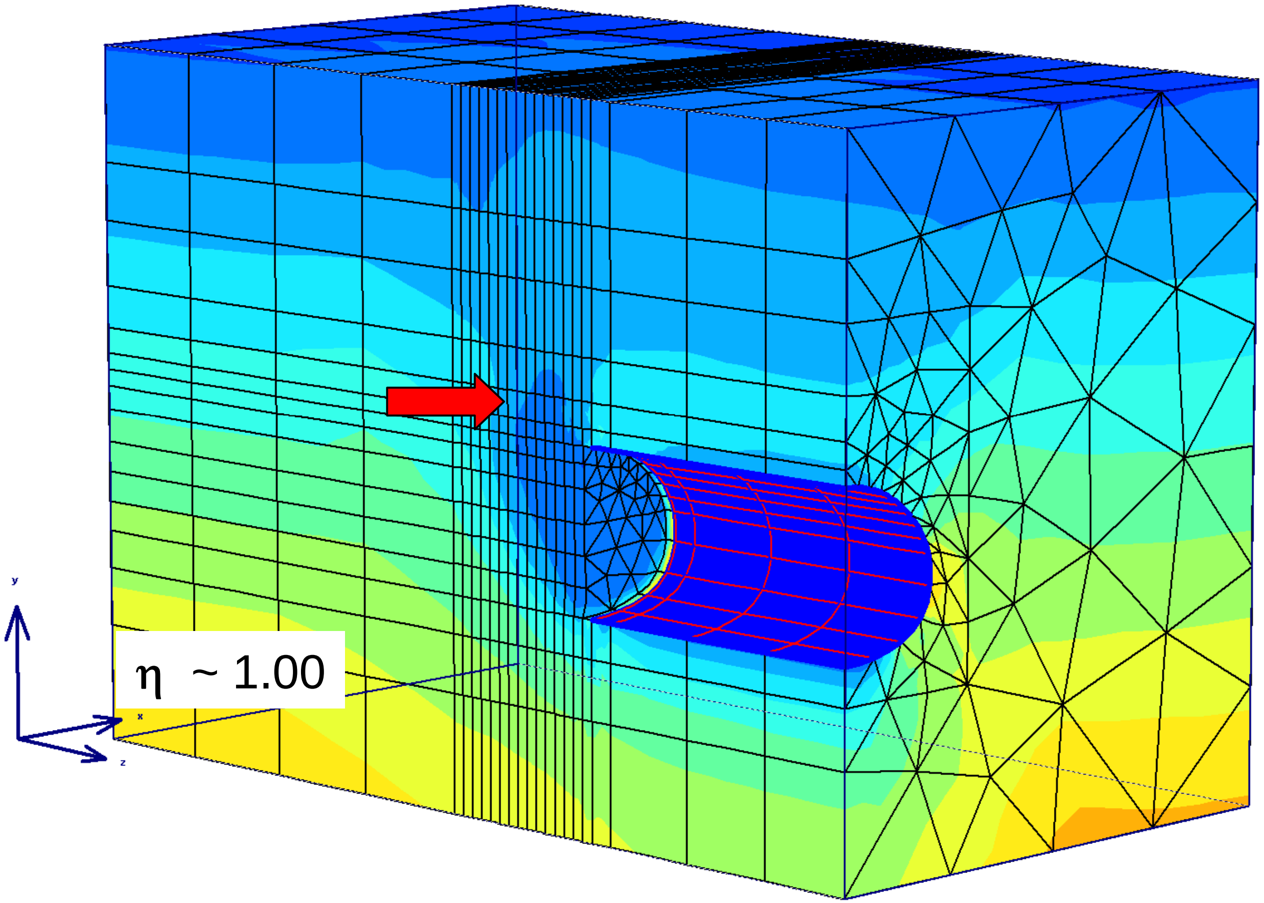

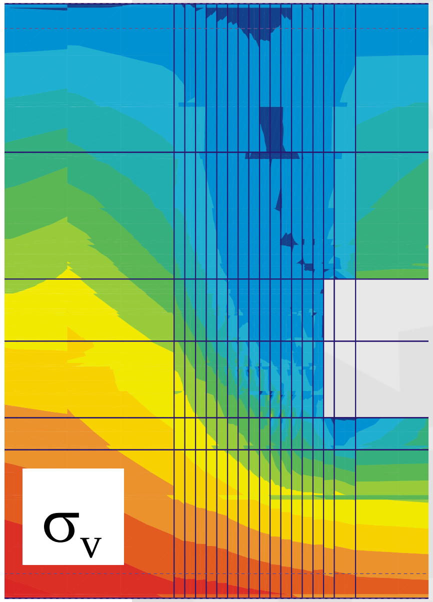

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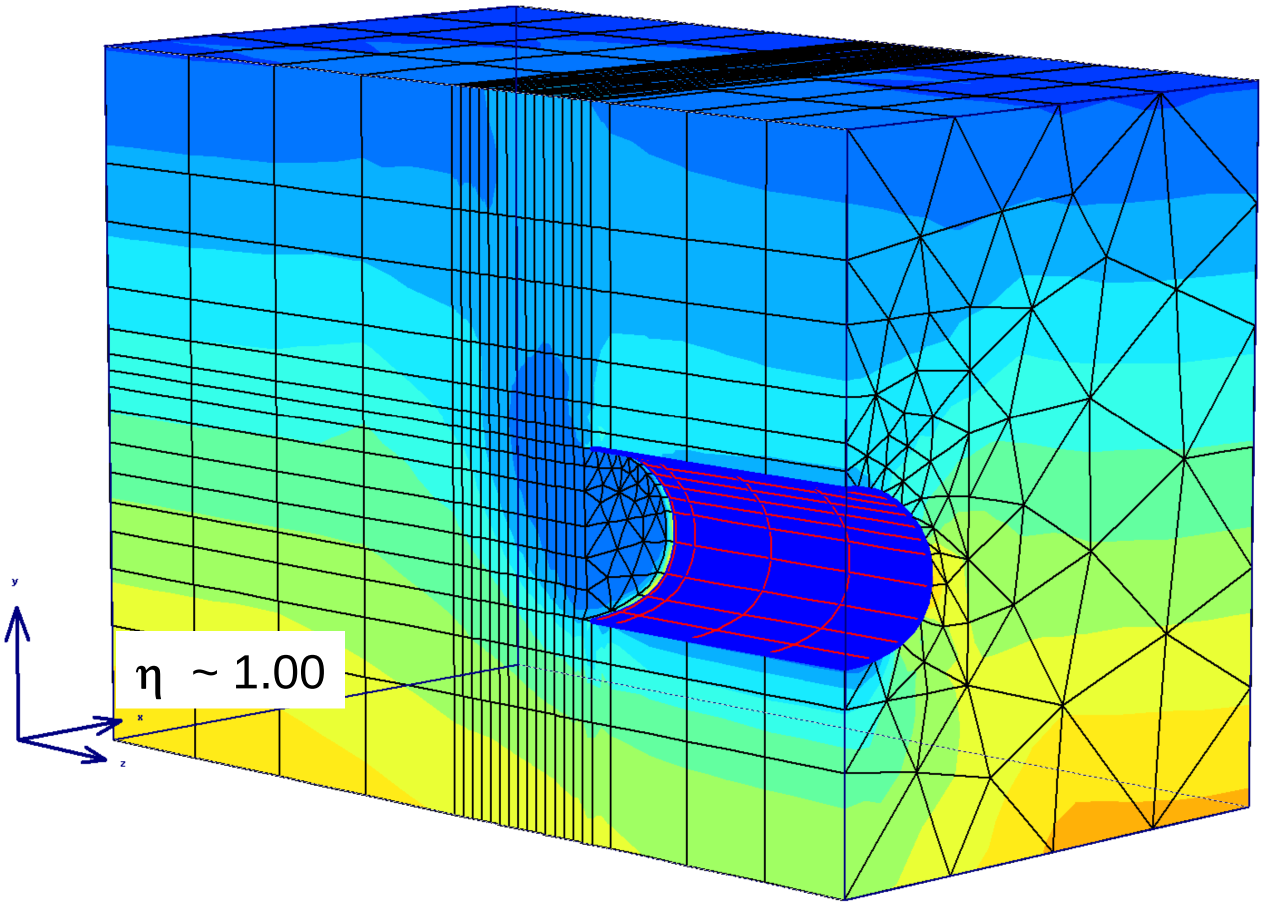
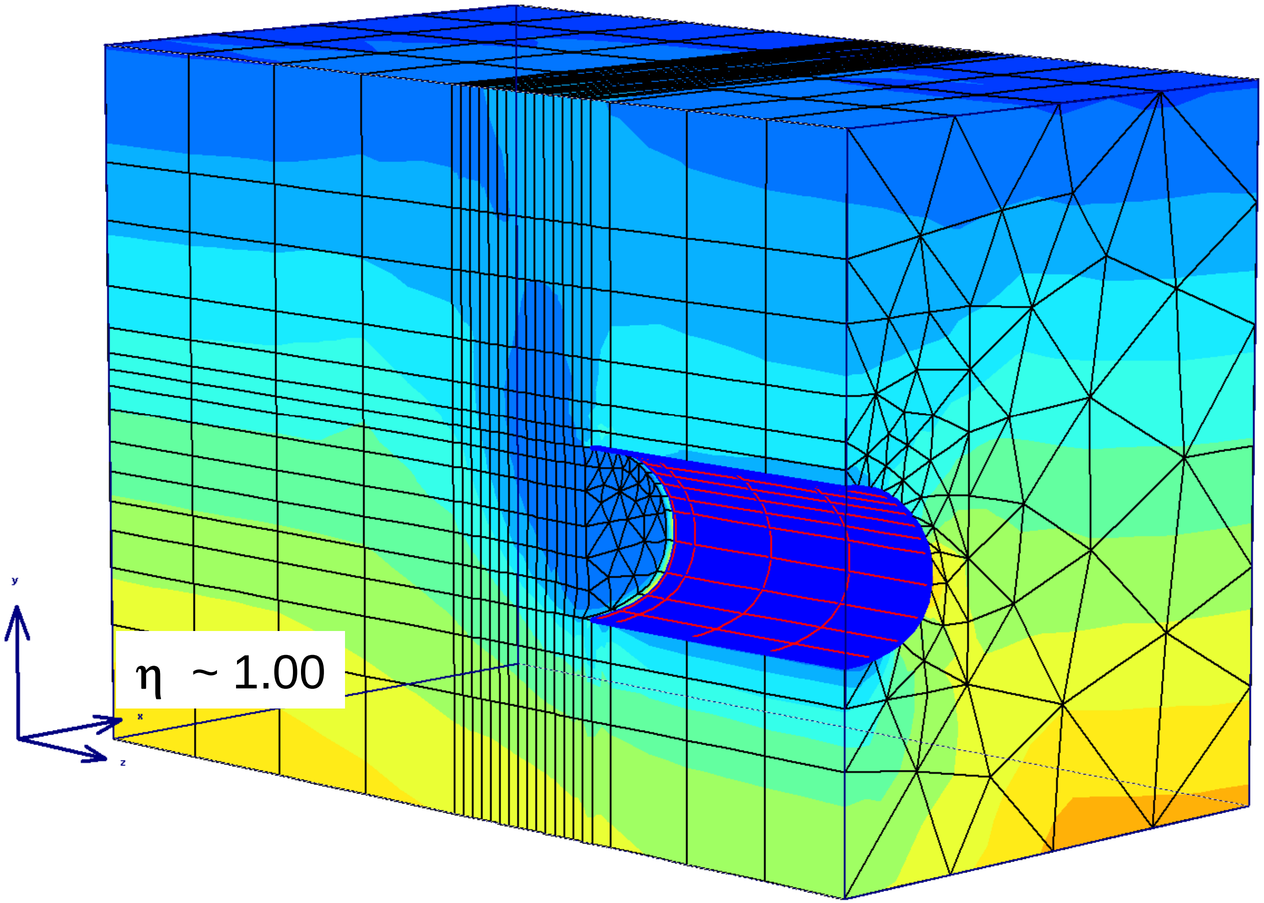


3D MODELLING - FACE STABILITY



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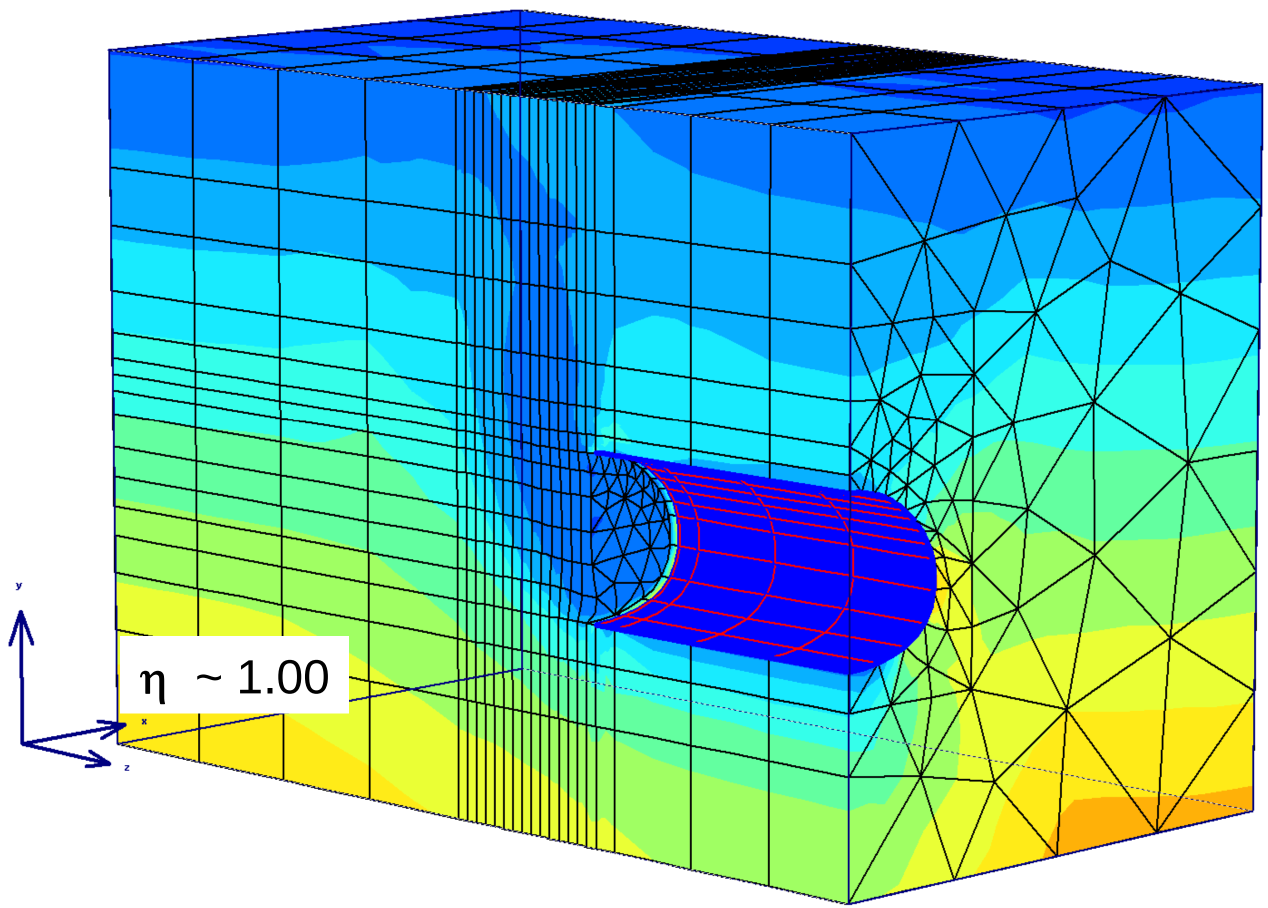

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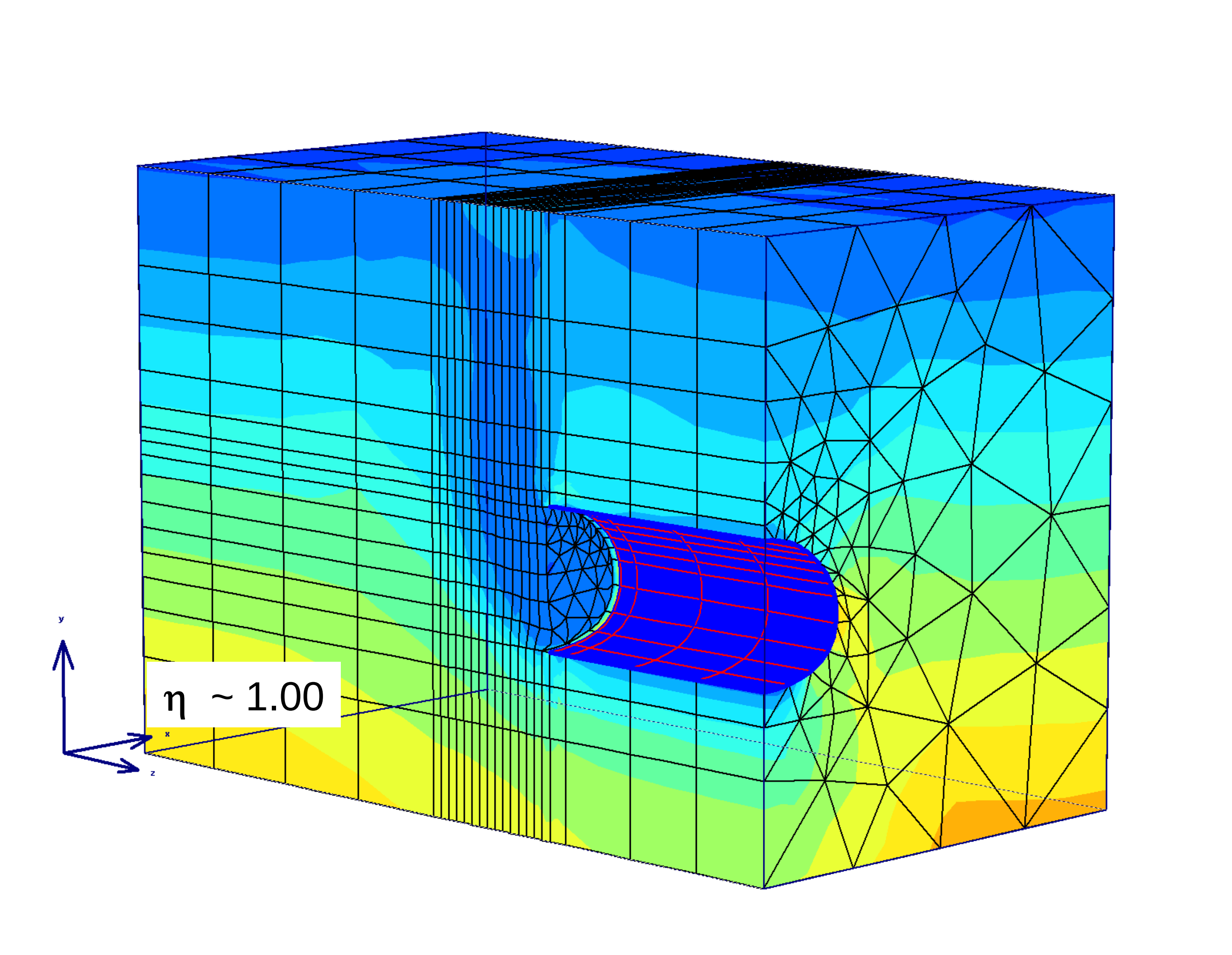

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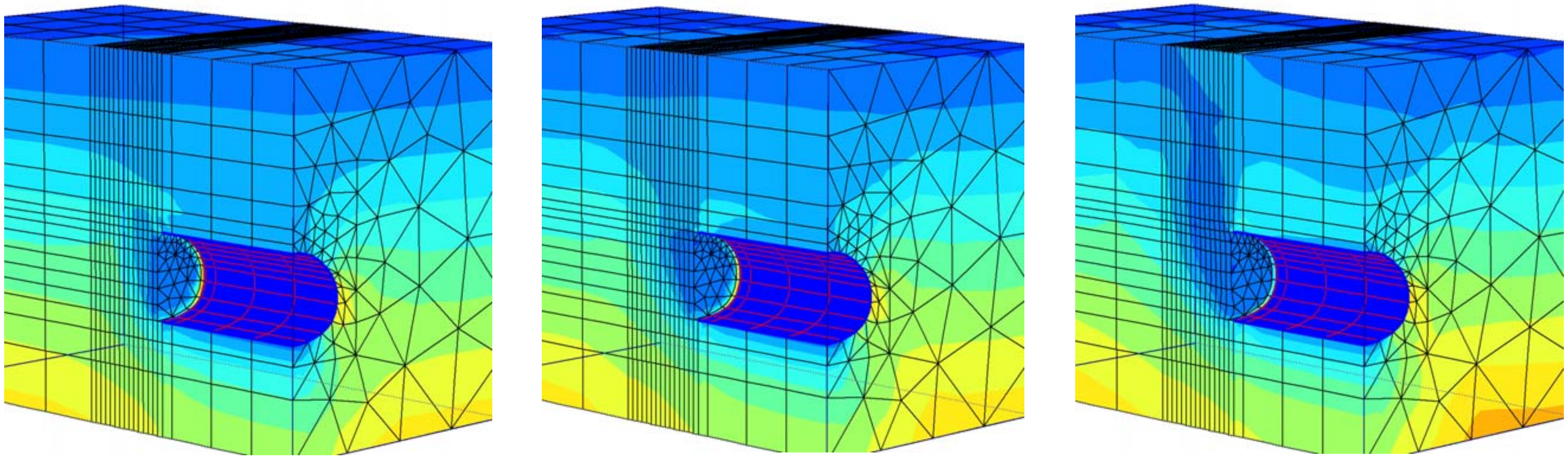
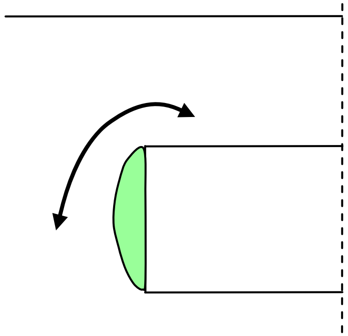
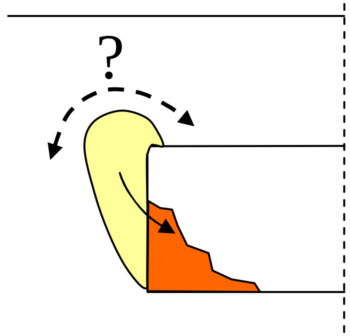


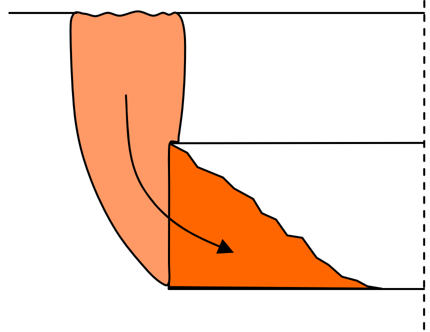
$\eta > 1.5$	$\eta \sim 1.1$	$\eta \sim 1.0$



working load condition

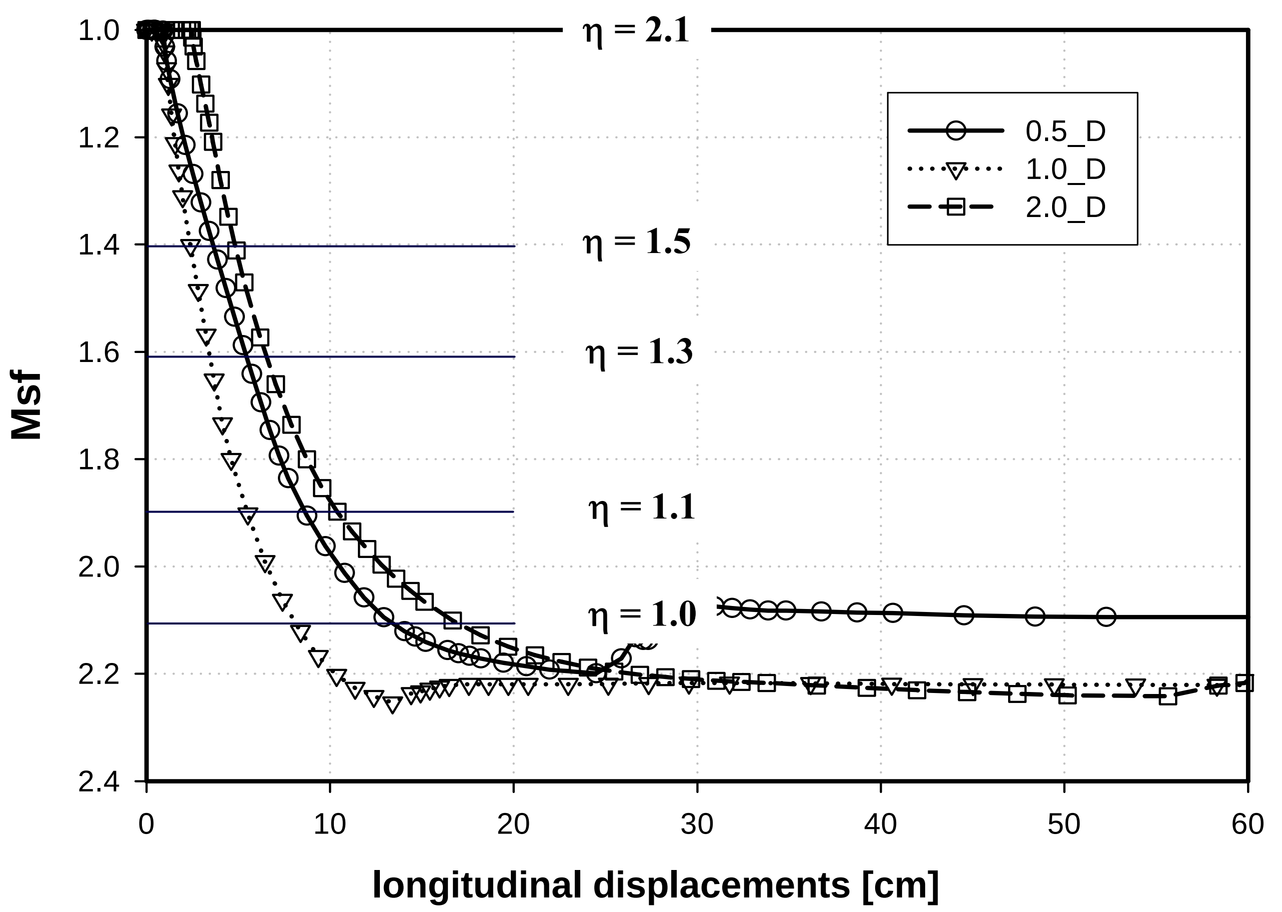


failure condition I



failure condition II

3D MODELLING - FACE STABILITY



SUMMARY FROM FACE STABILITY STUDY

Overburden height not critical for φ > 20°

(see also Vermeer, Ruse, Marcher ; Mayer et al., etc.)

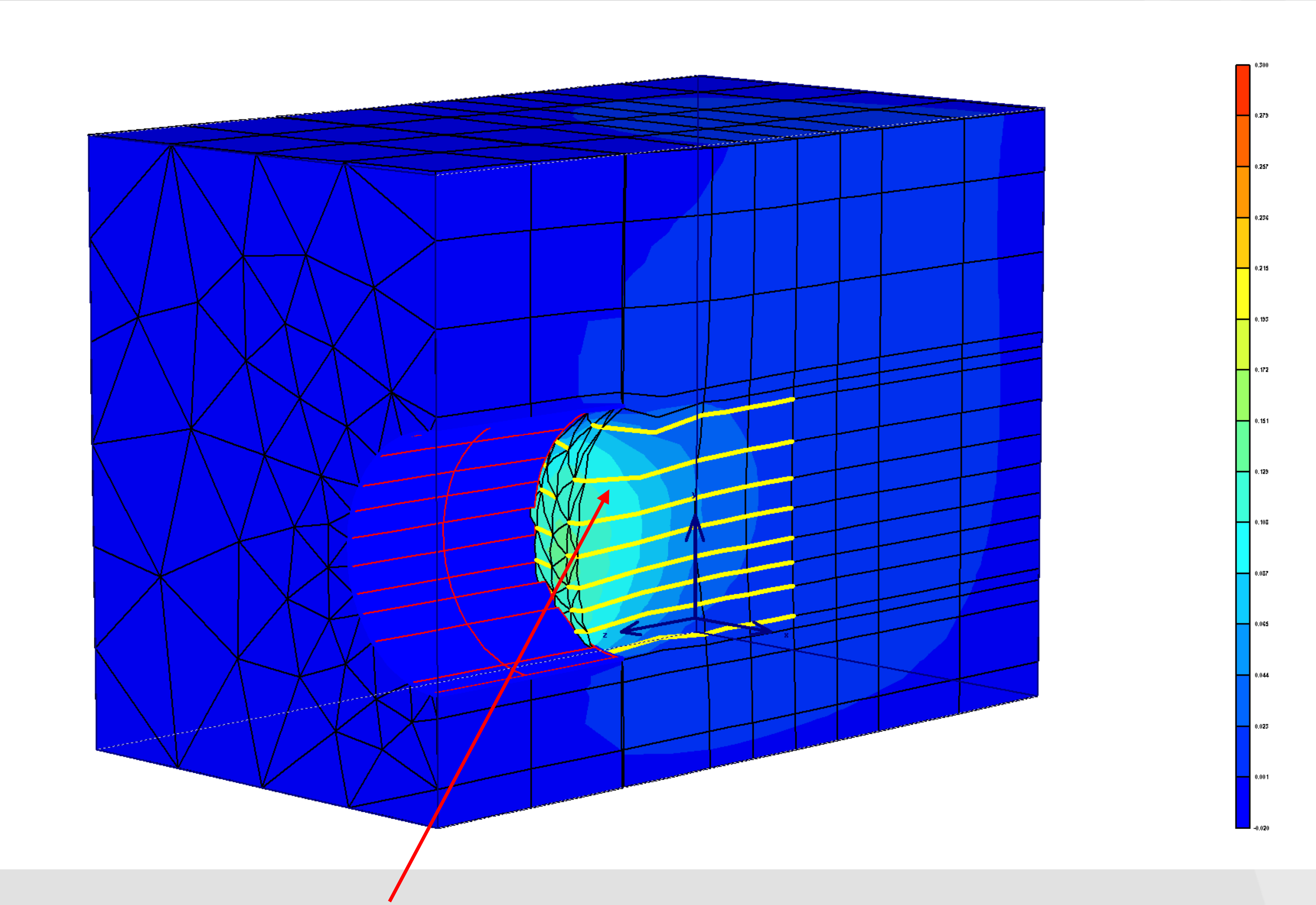
Tunnel diameter and cohesion important (φ > 20°)
approximate relationsship:

$c_{required} = \gamma \cdot D/10$ (Vermeer, Ruse, Marcher)

Deformation (longitudinal) even for failure condition I relatively small

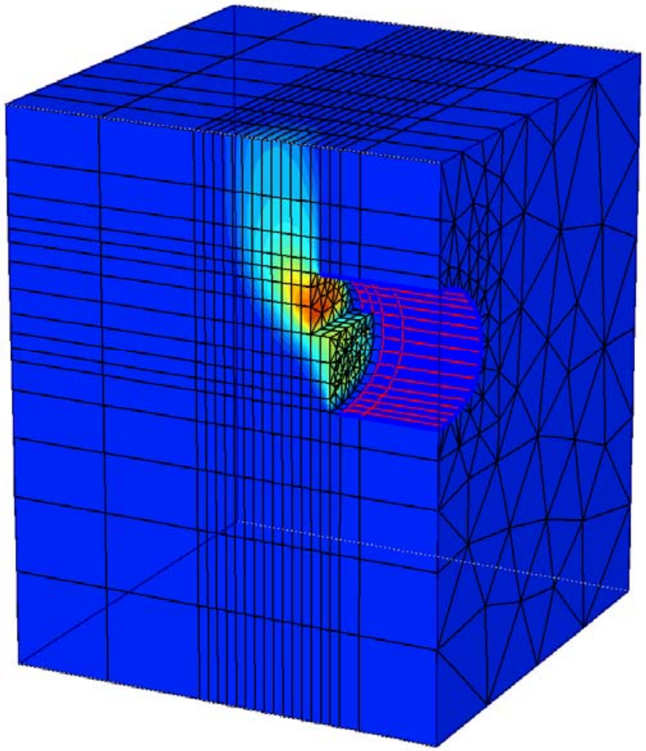
Up to failure condition II displacements increase progressively,
but safety margin is already low at failure condition I

FACE REINFORCEMENT

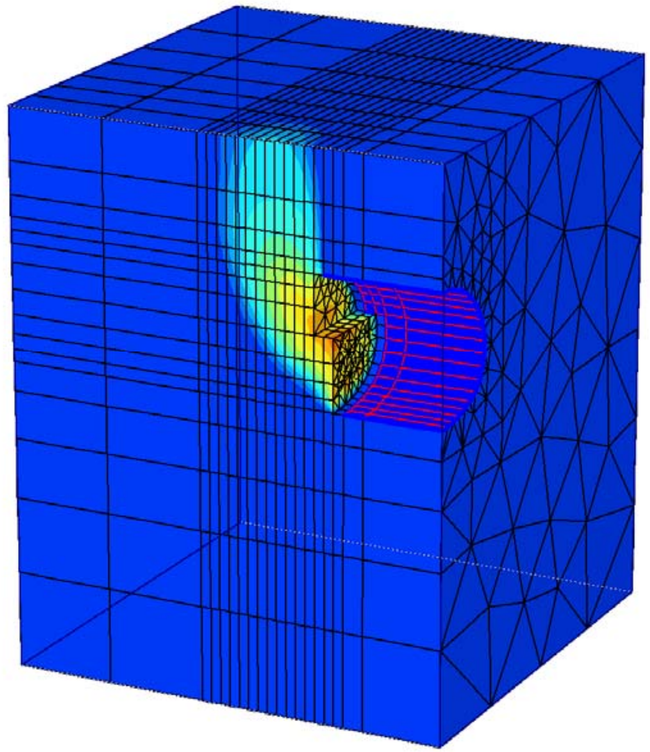


Face reinforcement with geotextile-elements

FACE REINFORCEMENT

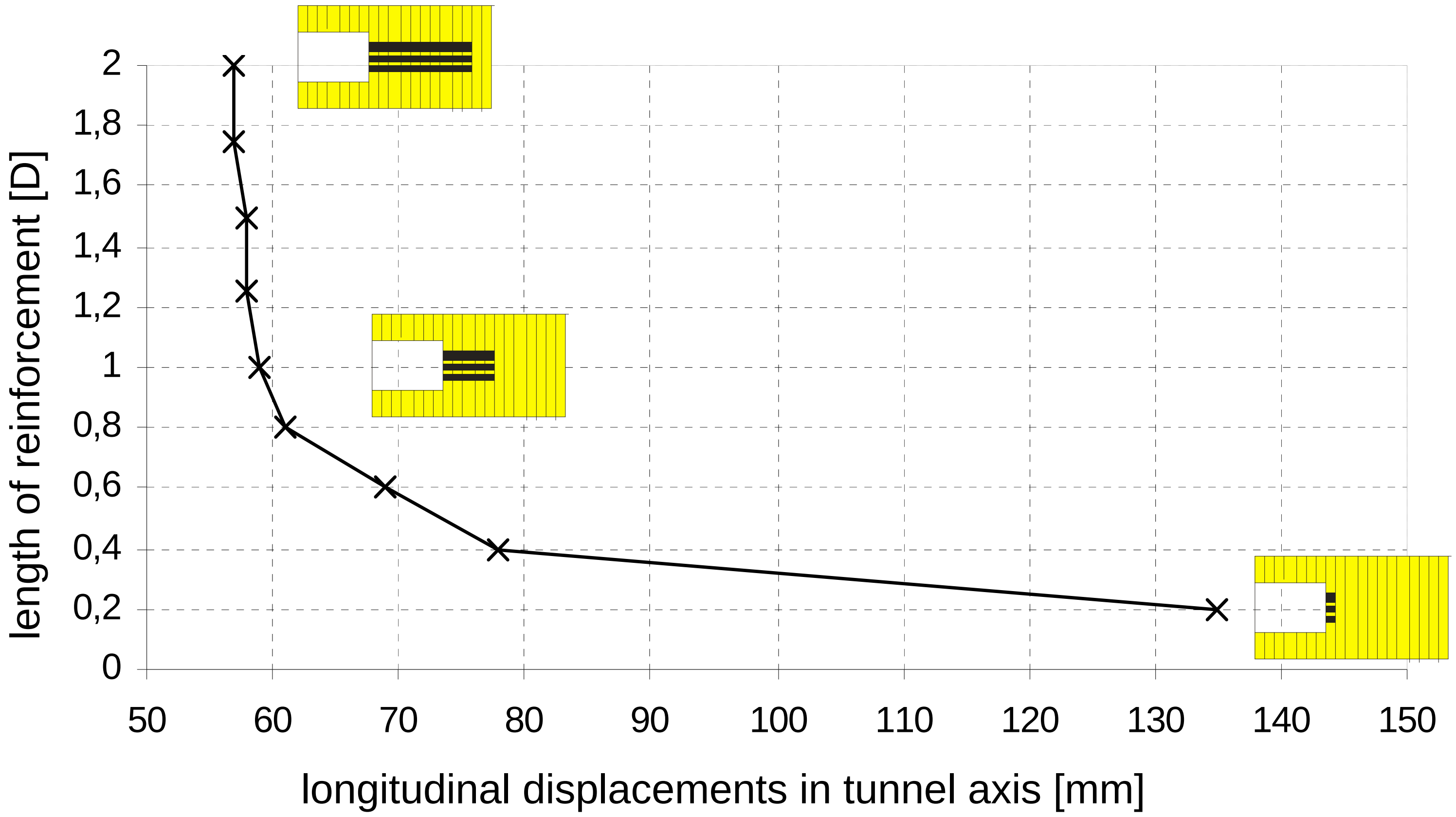


anchor length 12 m



anchor length 4 m

FACE REINFORCEMENT



Face reinforcement with geotextile-elements

SUMMARY

- **2D-analysis state-of-the-art in practice**

  > prerelaxation methods

  (load reduction method – stiffness reduction method)

- **Attention with boundary conditions**

  (in particular with MC-models)

- **Full 3D analysis for complex excavation sequence**

  leads to very large models

- **For face stability 3D - analysis required**