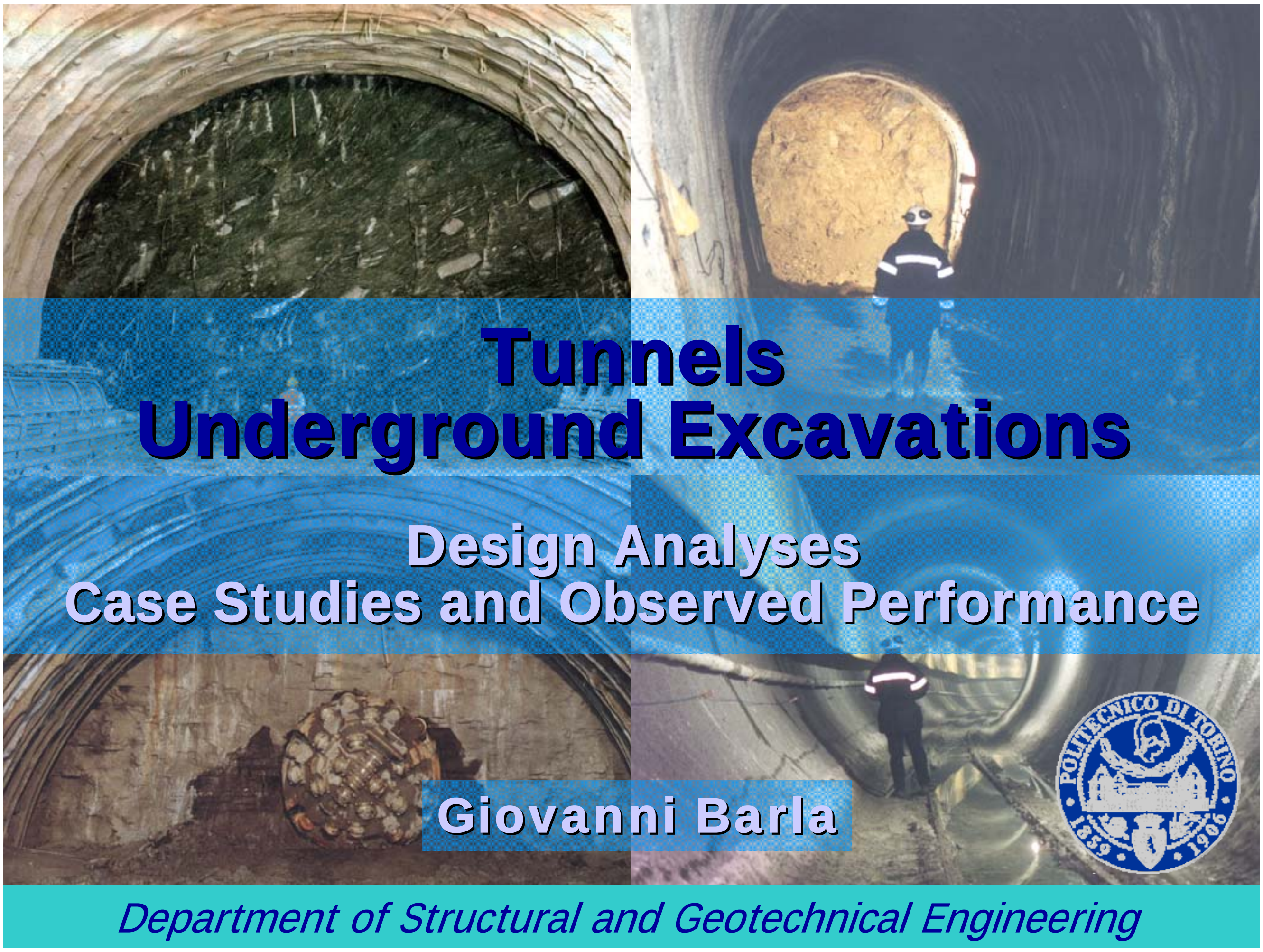
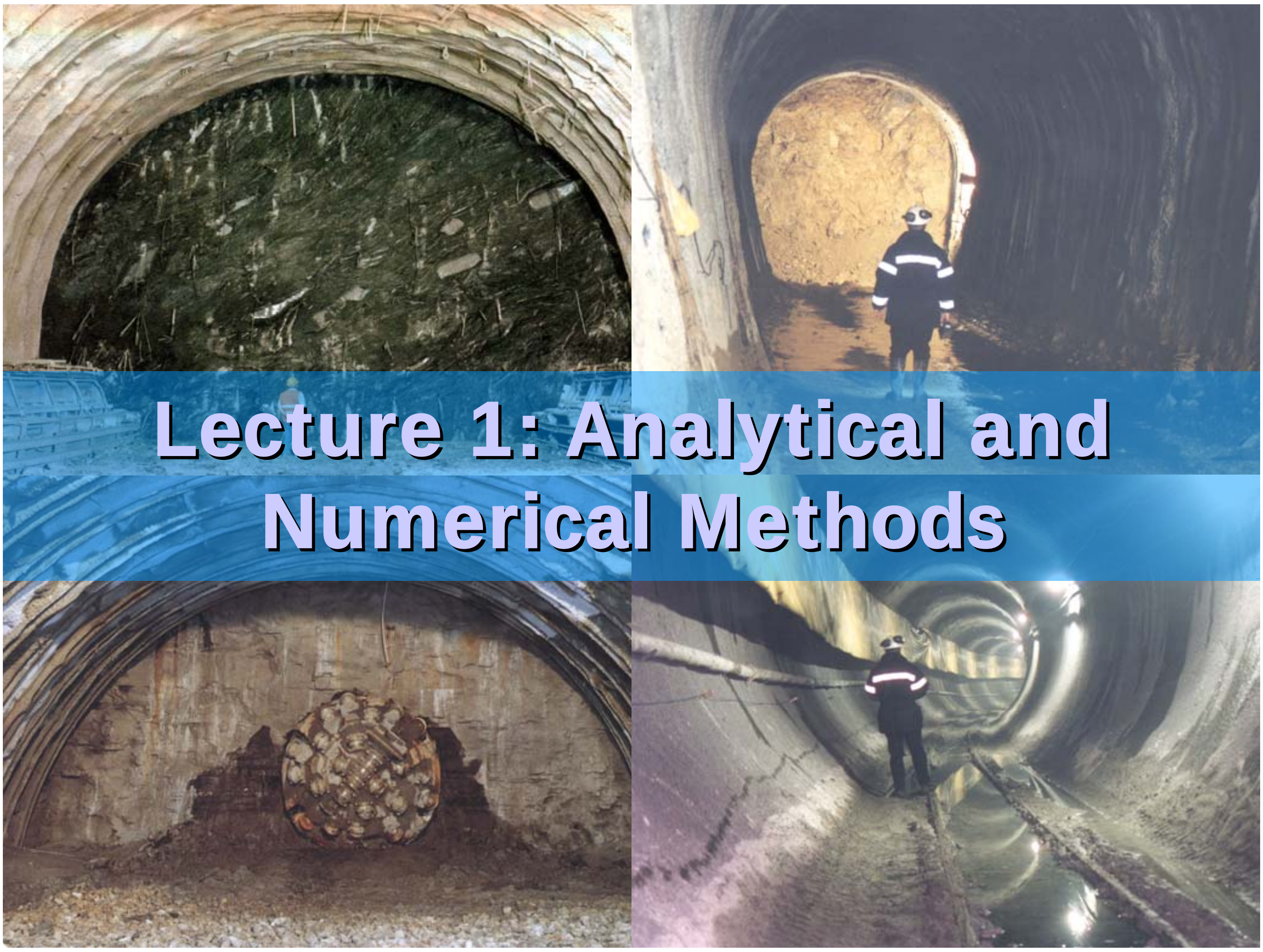


Tunnels
Underground Excavations
Design Analyses
Case Studies and Observed Performance
Giovanni Barla
POLITECNICO DI TORINO 1859 1906
Department of Structural and Geotechnical Engineering

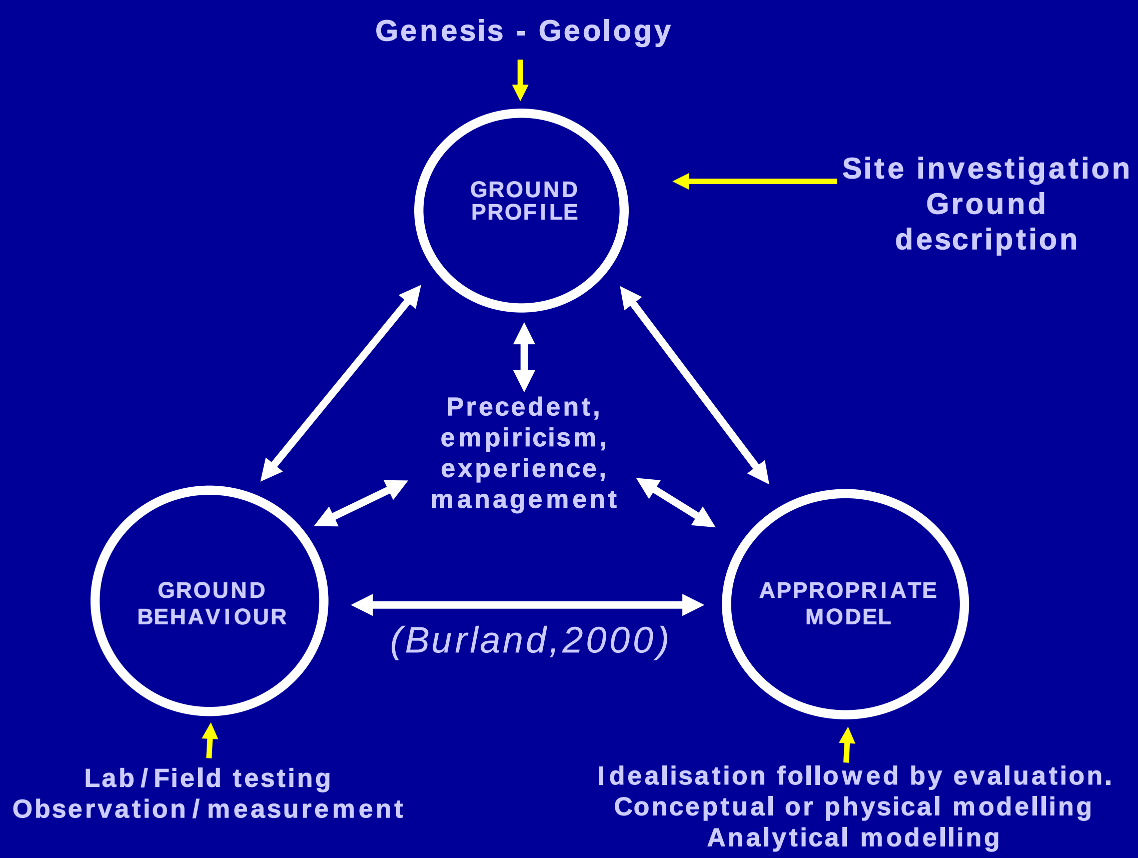


Lecture 1: Analytical and
Numerical Methods

Lecture Outline

- Geotechnical Triangle
- Interactive Design
- Continuum and Discontinuum Modelling
- Elastic and Elastoplastic Models
- Closed-form Solutions
- Numerical Methods

THE GEOTECHNICAL TRIANGLE



INTERACTIVE GEOTECHNICAL DESIGN

Final Design based on the most probable conditions (geology, hydrogeology, geotechnical parameters, construction methods,...)

Prediction of Rock Mass Behaviour without (intrinsic conditions) or with reinforcement / support measures (identify excavation cross sections)

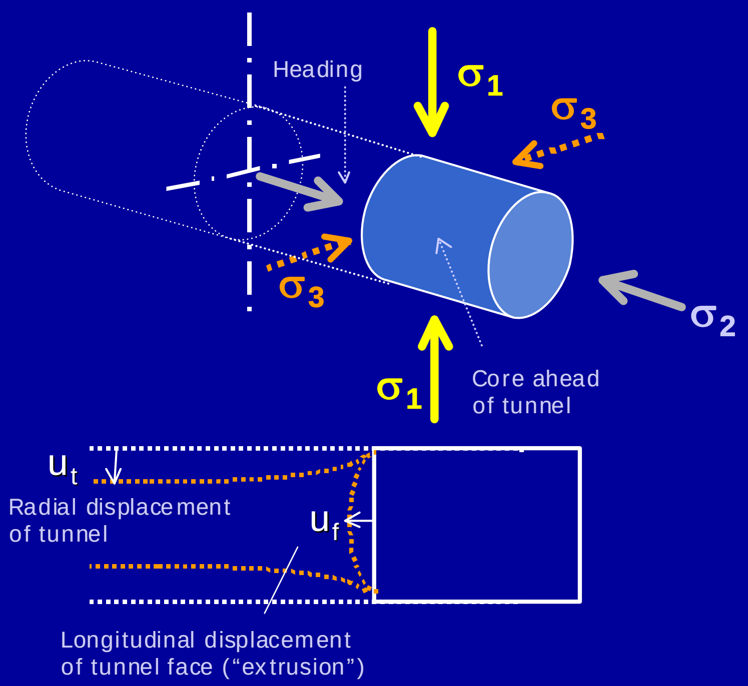
Perfomance Monitoring by a suitable well thought monitoring system to adopt during construction

---

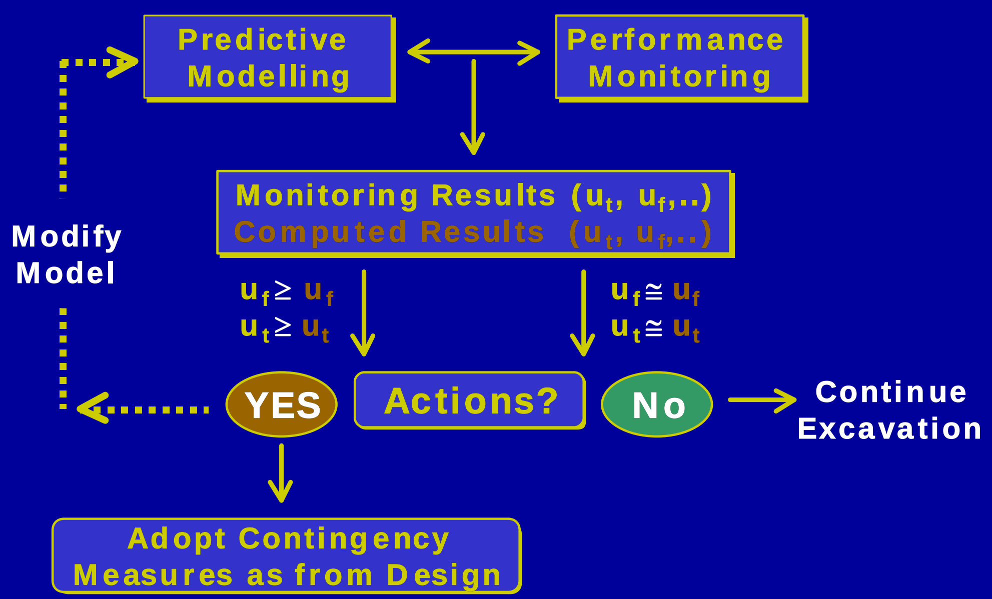
Prediction of Rock Mass Behaviour calls for the use of **Computational Models / Design Analyses**

There are no simple methods that can be adopted to predict the complex three-dimensional behaviour of underground structures, including the influence of reinforcement-support measures and rock mass-structure interaction

Tunnel Response during face advance



INTERACTIVE GEOTECHNICAL DESIGN



The following requirements shall be met before construction is started:

(1) The limits of behaviour which are acceptable shall be established

The following requirements shall be met before construction is started:

(2) The range of possible behaviour shall be assessed and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits

The following requirements shall be met before construction is started:

(3) A plan of monitoring shall be devised which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage and with sufficiently short intervals to allow contingency actions to be undertaken successfully

The following requirements shall be met before construction is started:

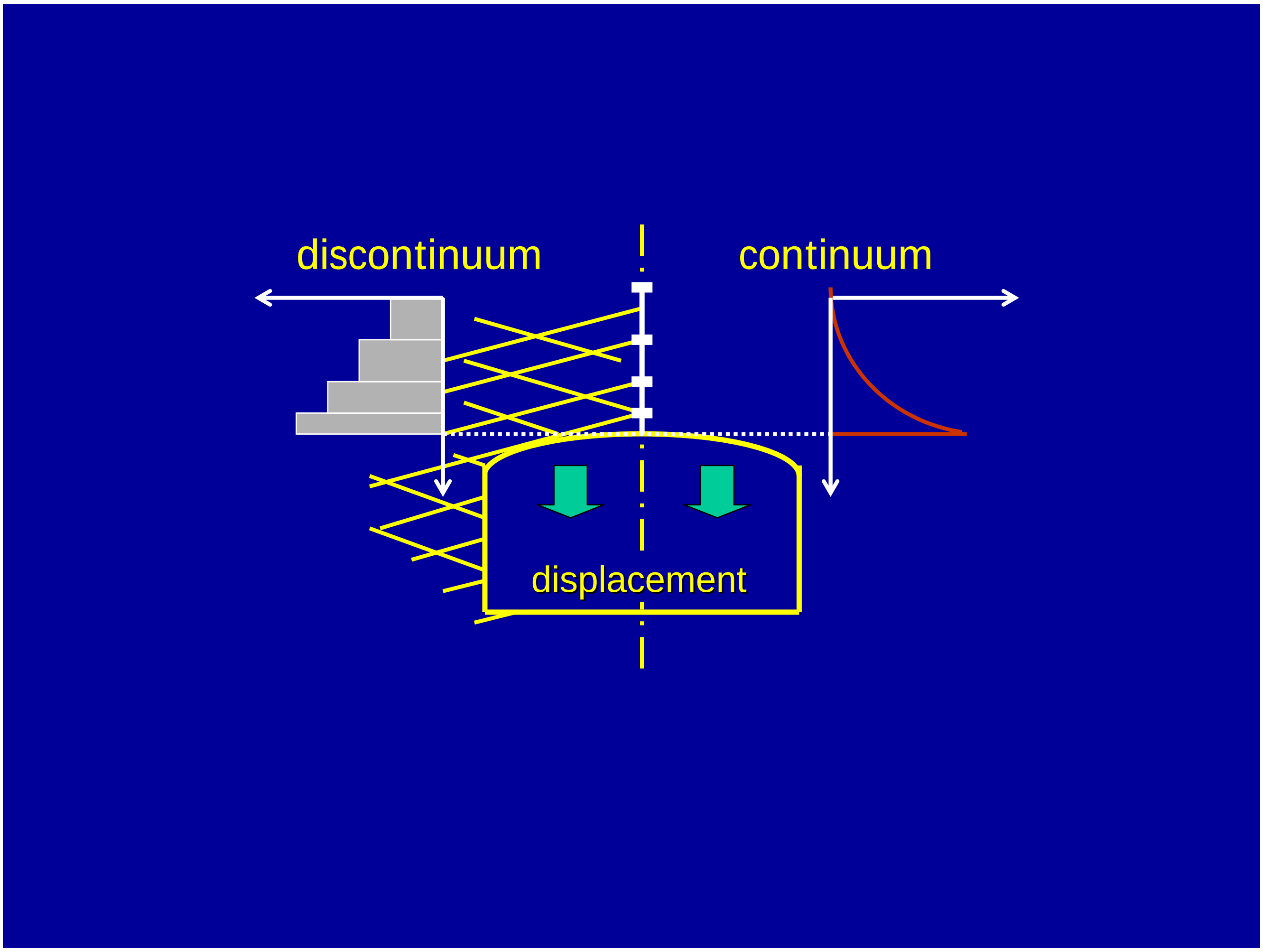
(4) The response time of the instruments and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system

The following requirements shall be met before construction is started:

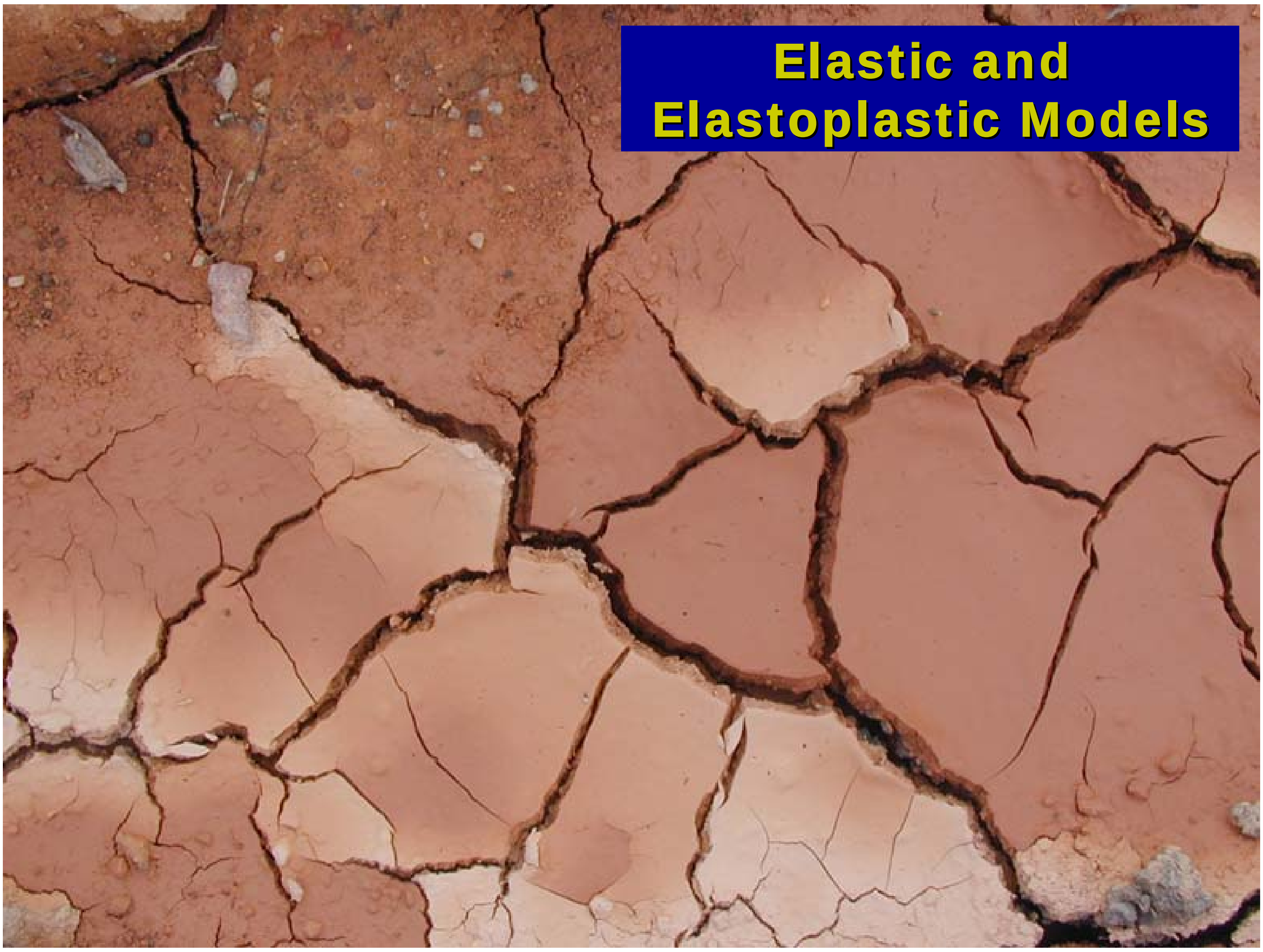
(5) a plan of contingency actions shall be devised which may be adopted if the monitoring reveals behaviour outside acceptable limits

Continuum and Discontinuum Modelling

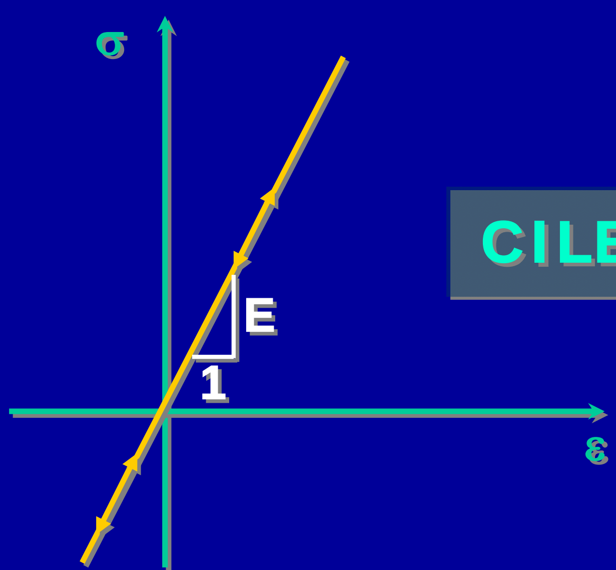

Carrara Marble
Calcschists
Calcareous Marl
Clay Shales
Flysch
Cataclastic
Rock/Carniole
Tectonised Gneiss
Contac Zone
ROCK
MASS
continuum
continuum
discontinuum
continuum
discontinuum
equivalent
continuum
dscontinuum
equivalent
continuum
equivalent
continuum
Design Parameters?
In Situ State of Stress?


discontinuum
continuum
displacement

Elastic and Elastoplastic Models



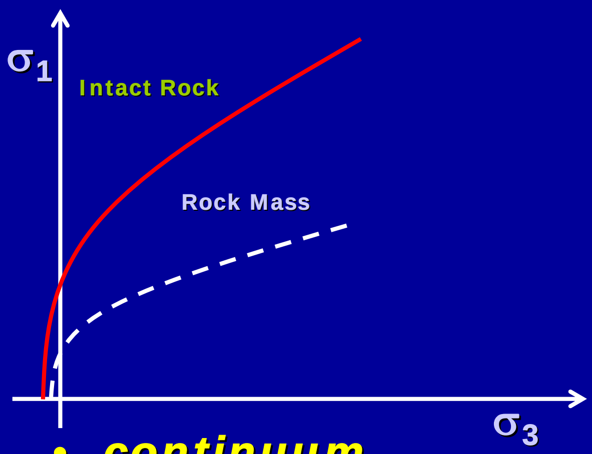
Continuum Isotropic Linearly Elastic (CILE)

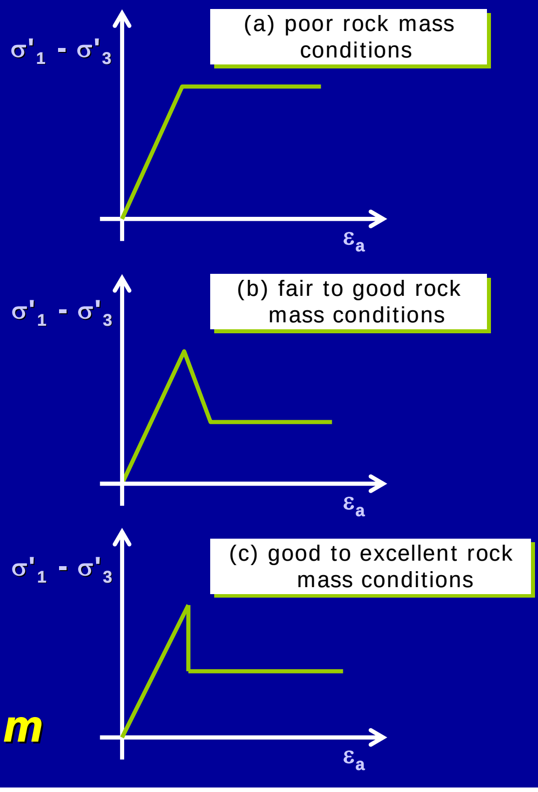


CILE

ELasto-PLAstic (ELPLA) Isotropic Continuum

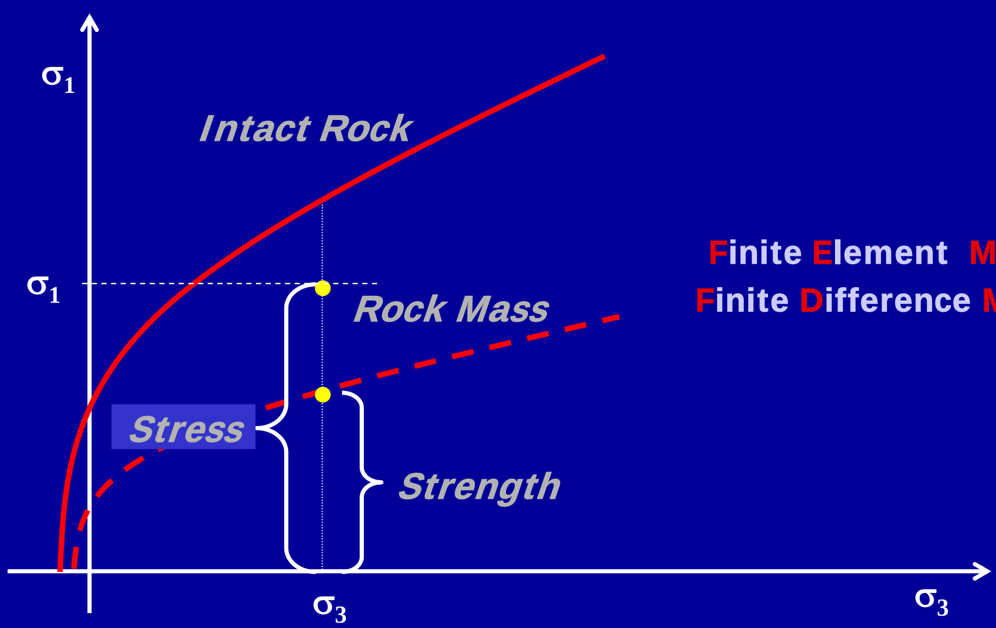
THE INTACT ROCK PROPERTIES NEED BE SCALED DOWN TO THE ROCK MASS PROPERTIES





- ***continuum***
- ***equivalent continuum***

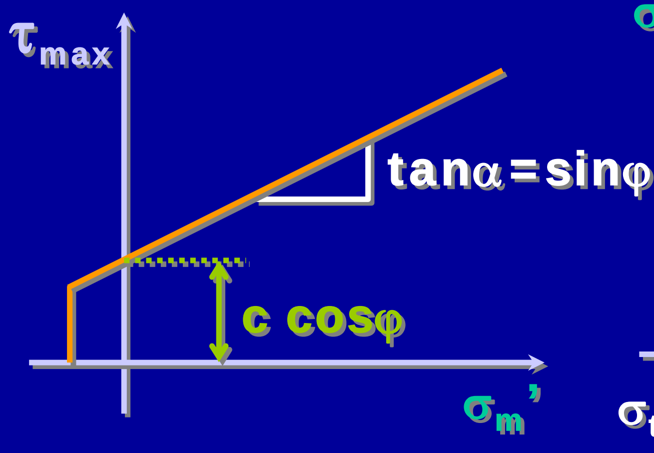
Illustration of the scaling process and definition of Factor of Safety



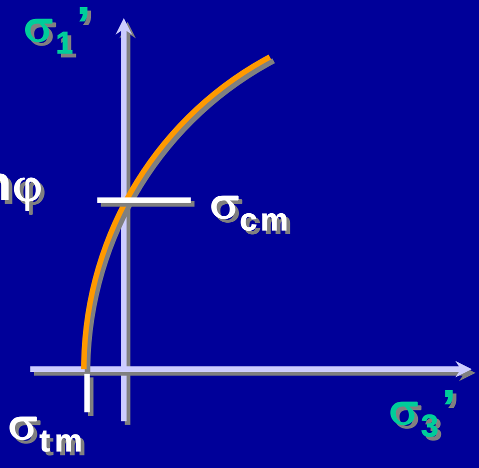
Finite Element Method

Finite Difference Method

CONTINUUM MODELLING



Mohr-Coulomb Criterion

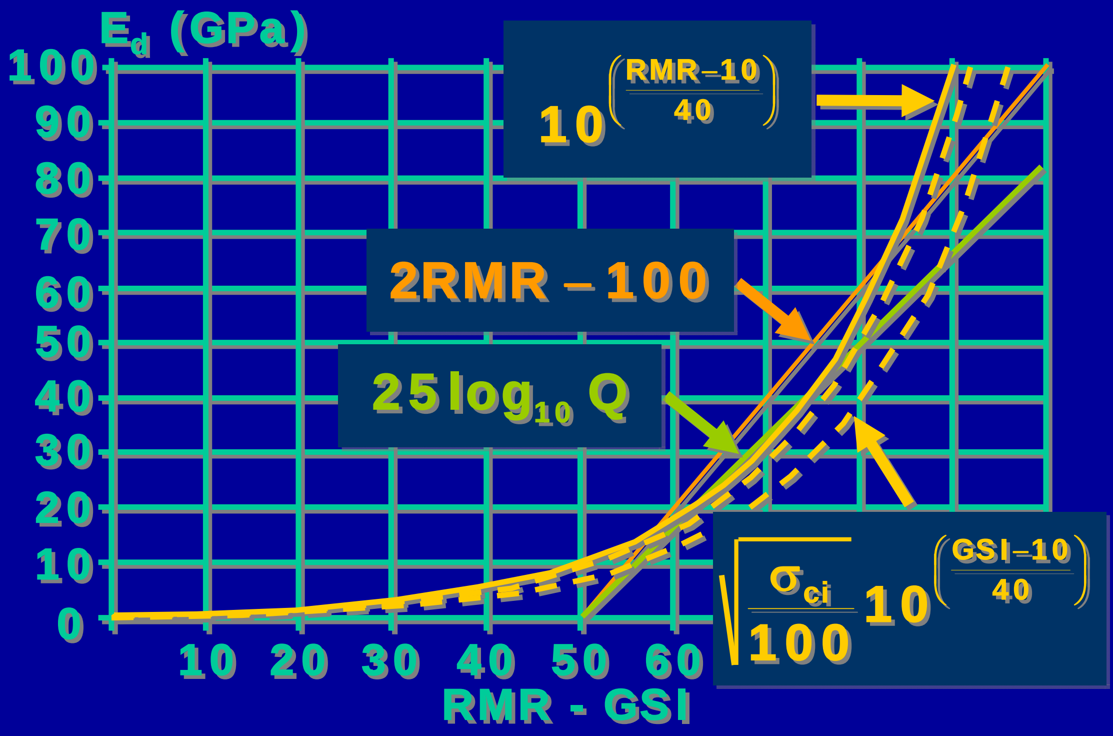


Hoek-Brown Criterion

Continuous Isotropic Linearly Elastic Medium (CILE)

For a CILE medium we need the following parameters:
the elastic (Young's) modulus E
and
the Poisson's ratio ν

Elastic Modulus E_d

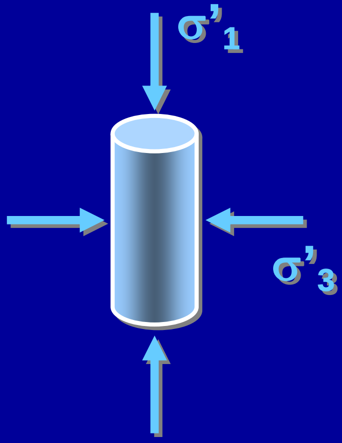


ELasto-PLAstic (ELPLA) Isotropic Continuum

In this case, we also need the following parameters:

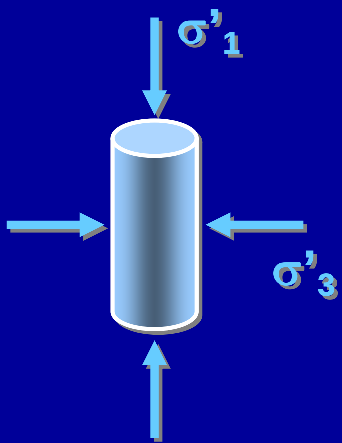
- for the M-C criterion: c, φ
- for the H-B criterion: σ_{ci}, m_b, s

Hoek and Brown criterion for the rock mass



$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_b \frac{\sigma_3'}{\sigma_{ci}} + s\right)^{\alpha}$$

σ_{ci} — intact rock uniaxial compressive strength



s, m_b — Hoek–Brown constants for the rock mass

α — exponent of the H-B criterion (usually α = 0.5)

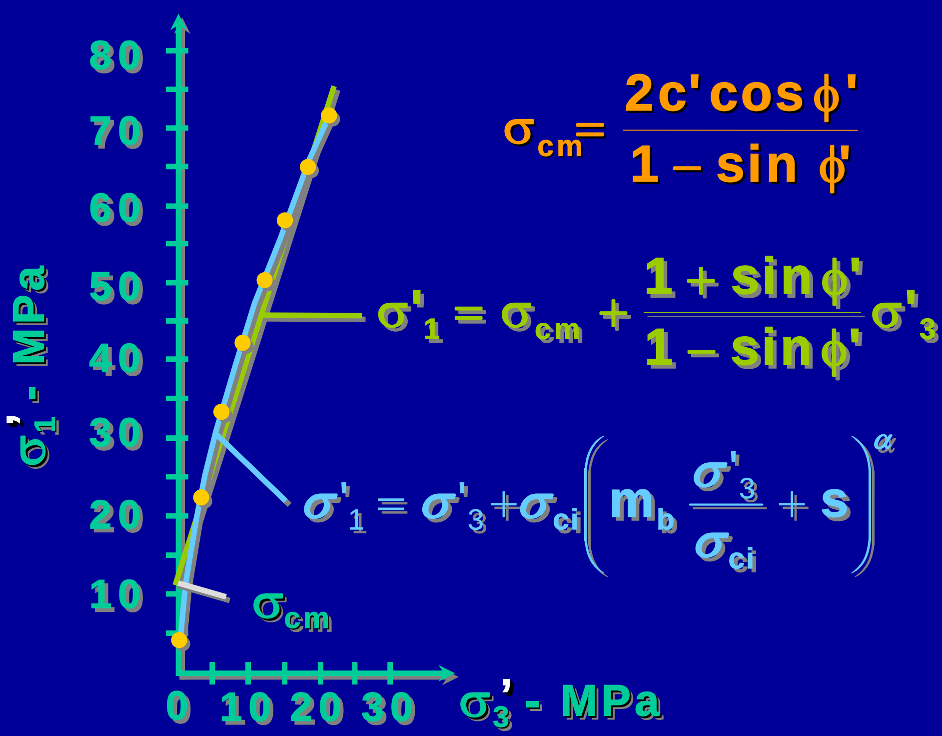
Linearization Procedure

$$\sigma'_1 = \sigma'_3 + \sigma_{ci}\left(m_b \frac{\sigma'_3}{\sigma_{ci}} + s\right)^{\alpha}$$

$$m_b = m_i \exp\left(\frac{GSI - 100}{28}\right)$$

$$s = \exp\left(\frac{GSI - 100}{9}\right)$$

σ_{ci} and m_i from uniaxial and triaxial laboratory tests



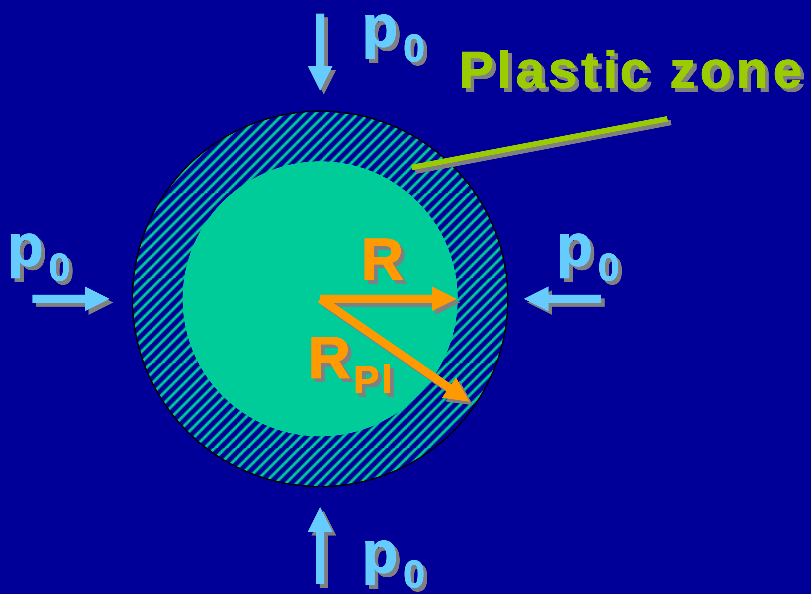
Design Analysis Methods

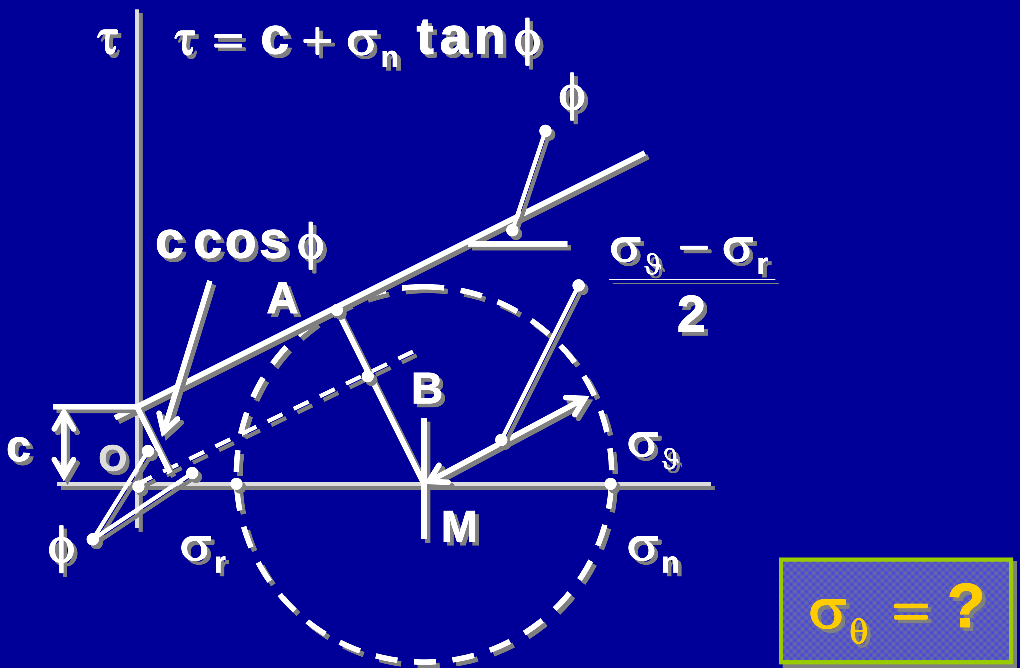
A ← (1) Closed form solutions
B ← (2) Numerical methods

A B CONTINUUM / EQUIVALENT CONTINUUM	B DISCONTINUUM

- Finite Element Method (FEM)
- Finite Difference Method (FDM)
- Boundary Element Method (BEM)
- Disitinct Element Method (DEM)

(a)Simplified solution





The result finally obtained is

with p_i

$$R_{pl} = R\left(\frac{(p_0 \sin\phi + c\cos\phi)(1-\sin\phi)}{p_i \sin\phi + c\cos\phi}\right)^{\frac{1-\sin\phi}{2\sin\phi}}$$

The result finally obtained is

with R_{pl}

$$p_i = \frac{1}{\sin\phi}\left((p_0 \sin\phi + c\cos\phi)(1-\sin\phi)\left(\frac{R}{R_{pl}}\right)^{\alpha} - c\cos\phi\right)$$

where $\alpha = \dfrac{2\sin\phi}{1-\sin\phi}$

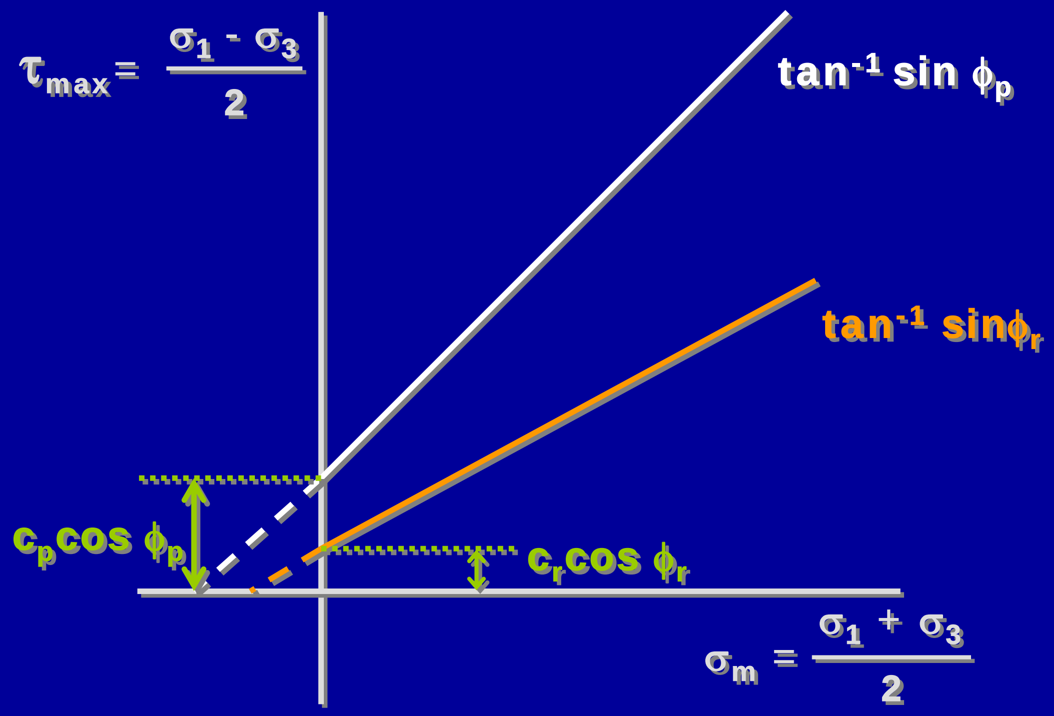
(b) Complete Solution

Assumptions

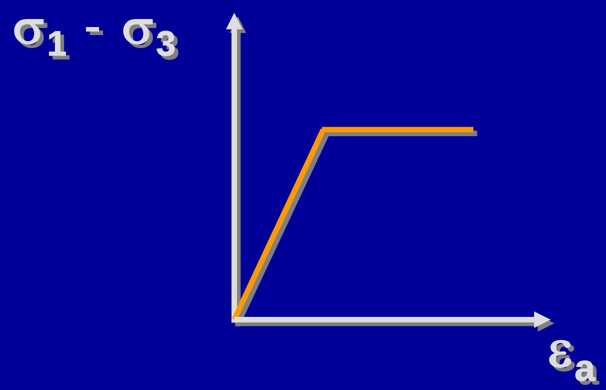
- Initial State of stress: isotropic $k_0 = 1$
- R.M. homogeneous and isotropic
- Deep circular tunnel
- Plane strain conditions

Constitutive Models
Closed Form Solutions

Mohr – Coulomb yield criterion

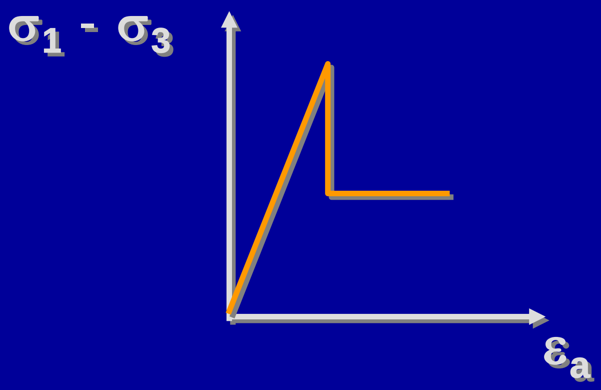


Constitutive Model 1



Elastic-plastic Ideally Plastic, for poor to fair rock mass quality

Constitutive Model 2



Elastic-plastic Ideally Brittle, for good to excellent rock mass quality

Equilibrium equation for axis-symmetric problem

1

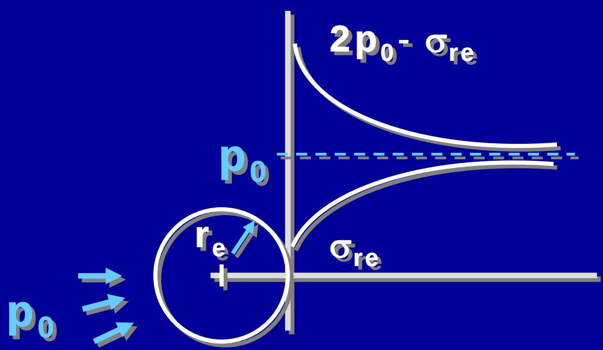
$$\frac{d\sigma_r}{dr} + \frac{\sigma_\vartheta - \sigma_r}{r} = 0$$

Lamé's Solution

State of stress in a CILE ground around a circular hole with radius r_e, inside pressure σ_{re} and at infinity p_o

2

$$\begin{cases} \sigma_\vartheta = p_0 + (p_0 - \sigma_{re})\left(\frac{r_e}{r}\right)^2 \\ \sigma_r = p_0 - (p_0 + \sigma_{re})\left(\frac{r_e}{r}\right)^2 \end{cases}$$



Strains ε_{re} ed $\varepsilon_{\vartheta e}$ in CILE

3

$$\begin{cases} \varepsilon_{re} = -\dfrac{1+\nu}{E}(p_0 - \sigma_{re}) \\ \varepsilon_{\vartheta e} = \dfrac{1+\nu}{E}(p_0 - \sigma_{re}) \end{cases}$$

Yield Criterion (Mohr - Coulomb)

4

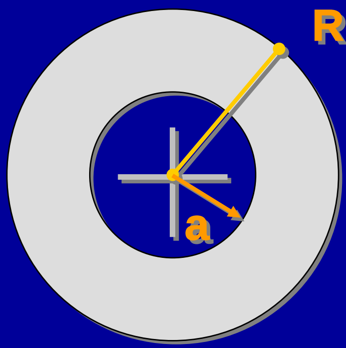
$$\begin{cases} \tau_{max} = c\cos\phi + \sigma_m \sin\phi \\ \sigma_1 = 2c\sqrt{N_\phi} + N_\phi \sigma_3 \\ N_\phi = \dfrac{1+\sin\phi}{1-\sin\phi} \end{cases}$$

peak: c_p, ϕ_p

residual: c_r, ϕ_r

1

Plastic Radius



$$p_{cr} = p_0(1 - \sin\phi_p) - c_p \cos\phi_p$$

Critical Pressure

$$R_{pl} = a\left\{\frac{(p_0 + c_r \cot g\phi_r)}{p_i + c_r \cot g\phi_r} - \frac{(p_0 + c_p \cot g\phi_p)\sin\phi_p}{p_i + c_r \cot g\phi_r}\right\}^{\frac{1}{N_r - 1}}$$

Plastic Radius

$$R_{pl} = a\left\{\frac{\left(p_0 + c_r \cot g\phi_r\right)}{p_i + c_r \cot g\phi_r} - \frac{\left(p_0 + c_p \cot g\phi_p\right)\sin\phi_p}{p_i + c_r \cot g\phi_r}\right\}^{\frac{1}{N_r - 1}}$$

NOTE

For $c_p = c_r$ and $\phi_p = \phi_r$
We obtain the simplified solution (a)

Compute the radial displacement in the elastic zone,
i.e. for $r \geq R_{pl}$

$$u_r = \frac{1+\nu}{E} \cdot \left(p_0 - p_{cr}\right) \cdot \frac{R_{pl}^2}{r}$$

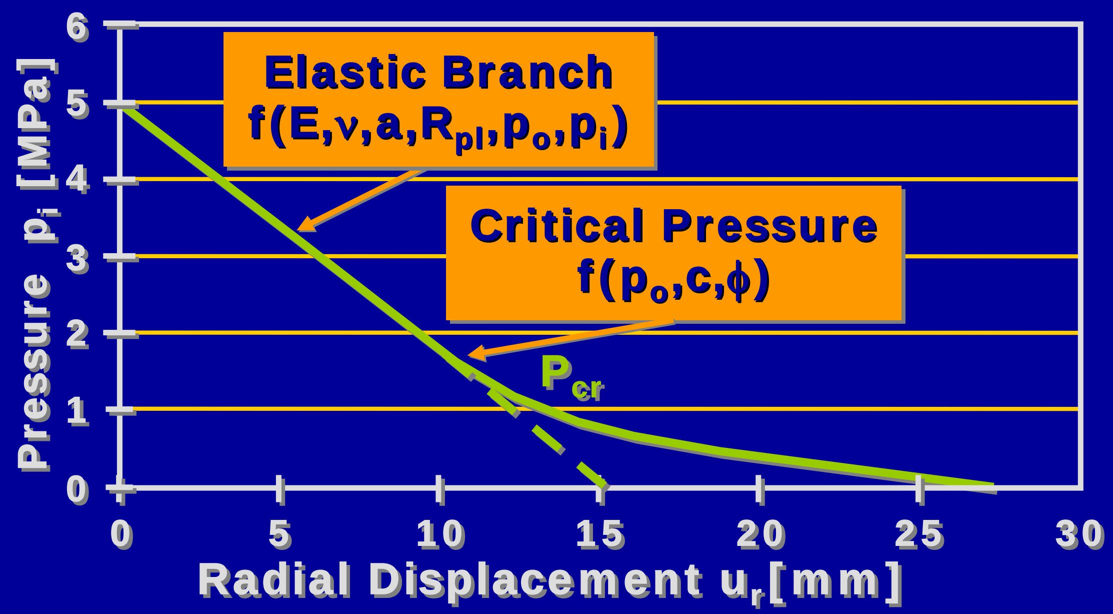
Compute the radial displacement in the plastic zone, i.e. for a ≤ r ≤ Rpl

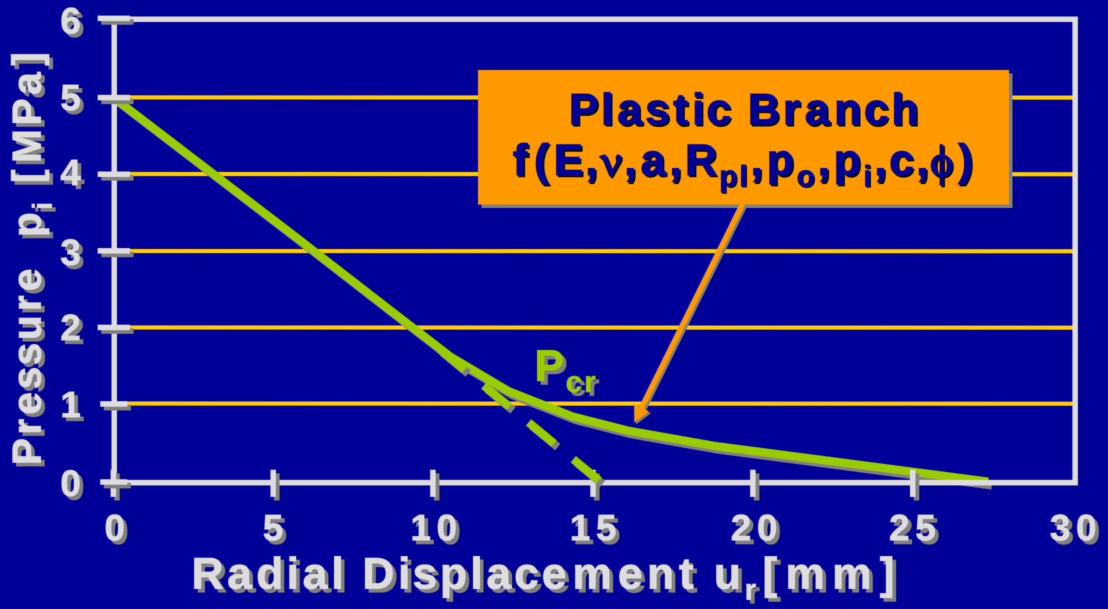
$$u_r = \frac{1+\nu}{E}\left\{\frac{R_{pl}^{k+1}}{r^k}(p_0 + c_p \cot g\phi_p)\sin\phi_p + \right.$$

$$+ (1-2\nu)(p_0 + c_r \cot g\phi_r)\left(\frac{R_{pl}^{k+1}}{r^k} - r\right) +$$

$$- \frac{(p_i + c_r \cot g\phi_r)[1 + N_r k - \nu(k+1)(1+N_r)]}{(N_r + k)a^{N_r - 1}} \cdot$$

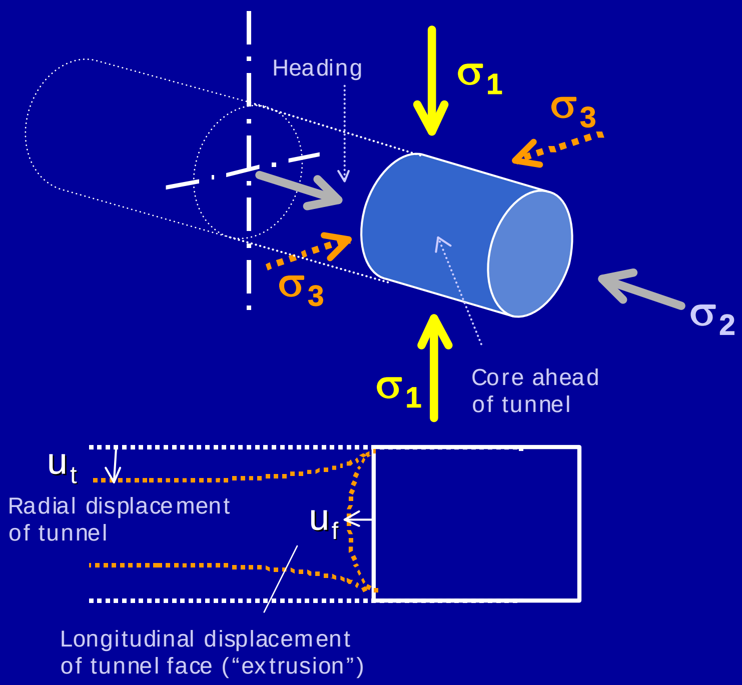
$$\left.\cdot\left[\frac{R_{pl}^{(N_r+k)}}{r^k} - r^{N_r}\right]\right\} \qquad N_r = \frac{1+\sin\phi_r}{1-\sin\phi_r}\ ; \quad k = \frac{1+\sin\psi}{1-\sin\psi}$$





The **characteristic curve (ground reaction curve)** gives a relationship between the radial displacement u_r at the tunnel contour and the applied pressure p_i

Tunnel Response during face advance



$$u_r = \lambda(x)\, u_r(\infty) = \lambda(x)\,[\,(p_0 a) \,/\, (2G)\,]$$

$$\lambda(x) = 0{,}28 + 0{,}72\left[1 - \left(\frac{0{,}84a}{0{,}84a + x}\right)\right]$$

Panet & Guenot (1982)

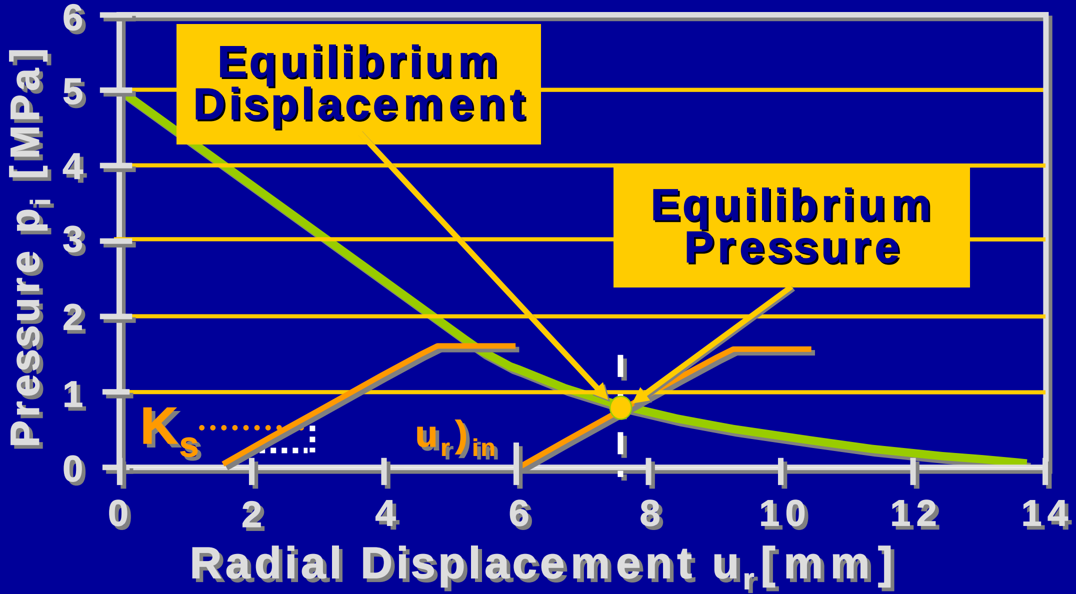
ILE ground

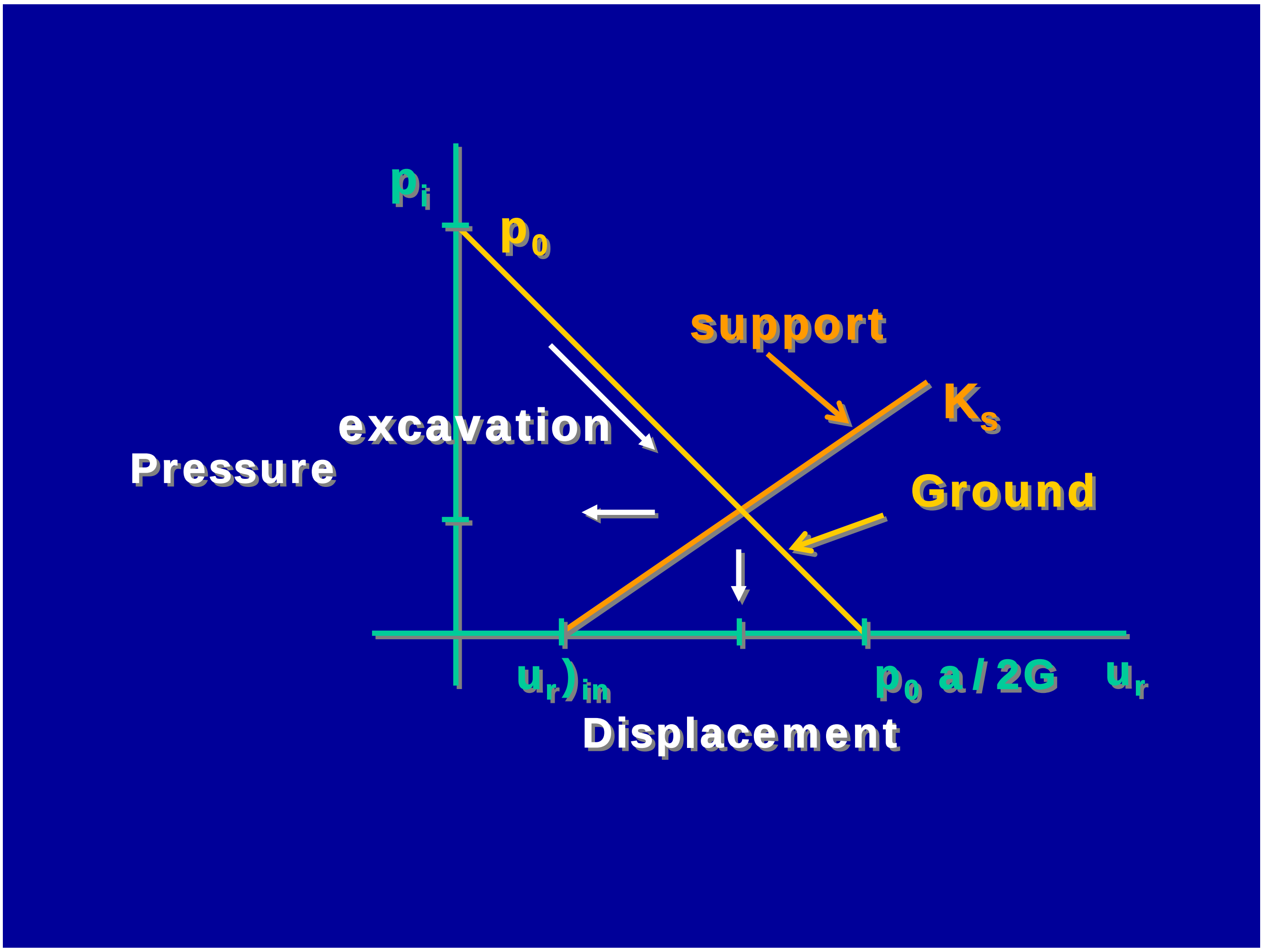
$$\left.\begin{aligned} u_r &= \lambda(x)\, u_r(\infty) \\ \lambda(x) &= 1 - \left(\frac{1}{1 + \frac{x}{0{,}84 R_{pl}}} \right)^2 \end{aligned}\right\}$$

Panet & Guenot (1982)

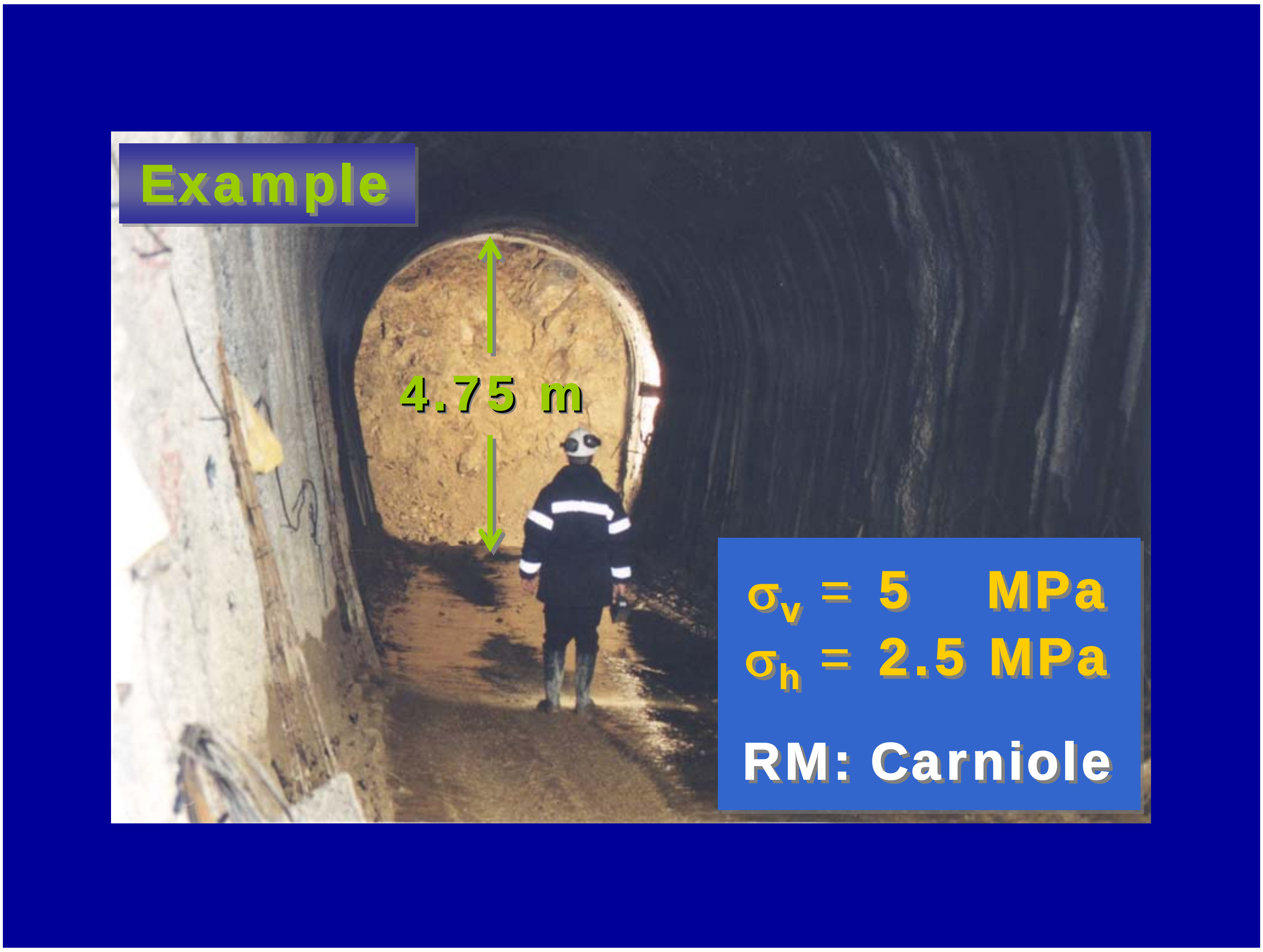
ELPLA ground

Ground reaction

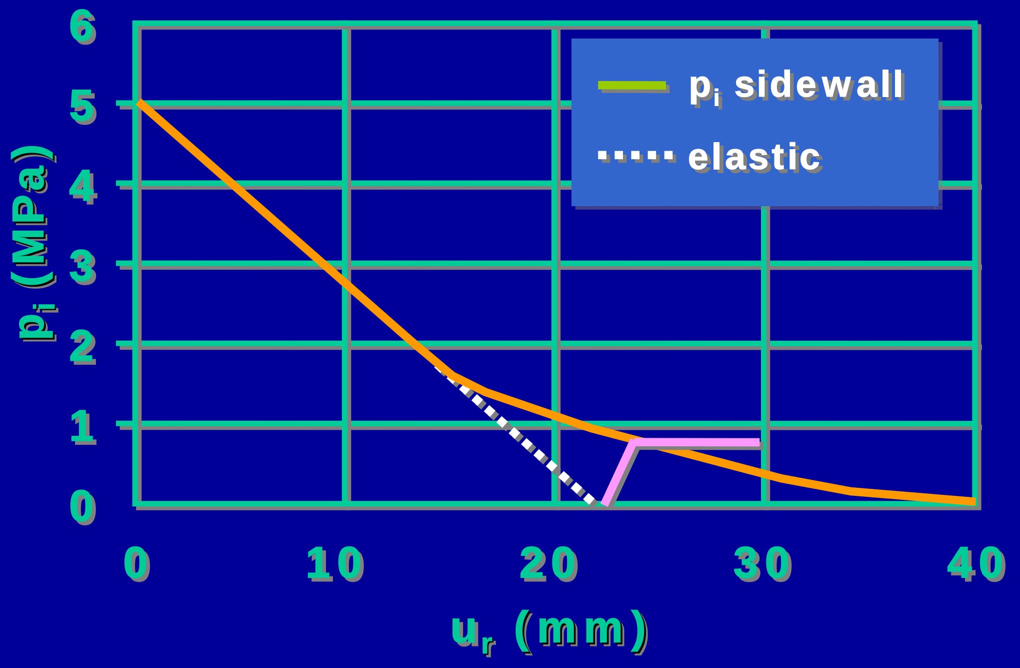




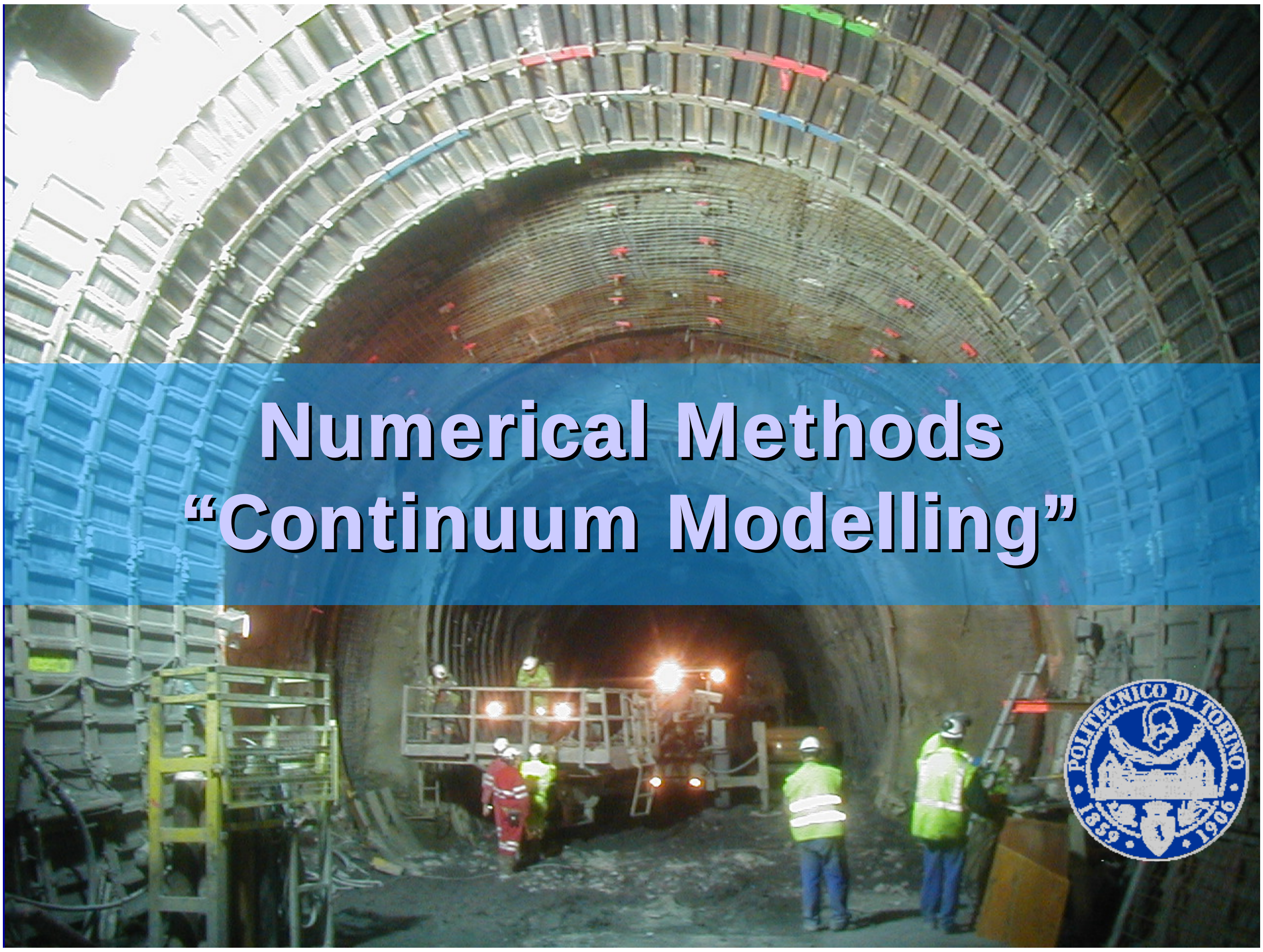
p_i
p_0
support
K_s
excavation
Pressure
Ground
$u_r)_{in}$
$p_0\ a / 2G$
u_r
Displacement



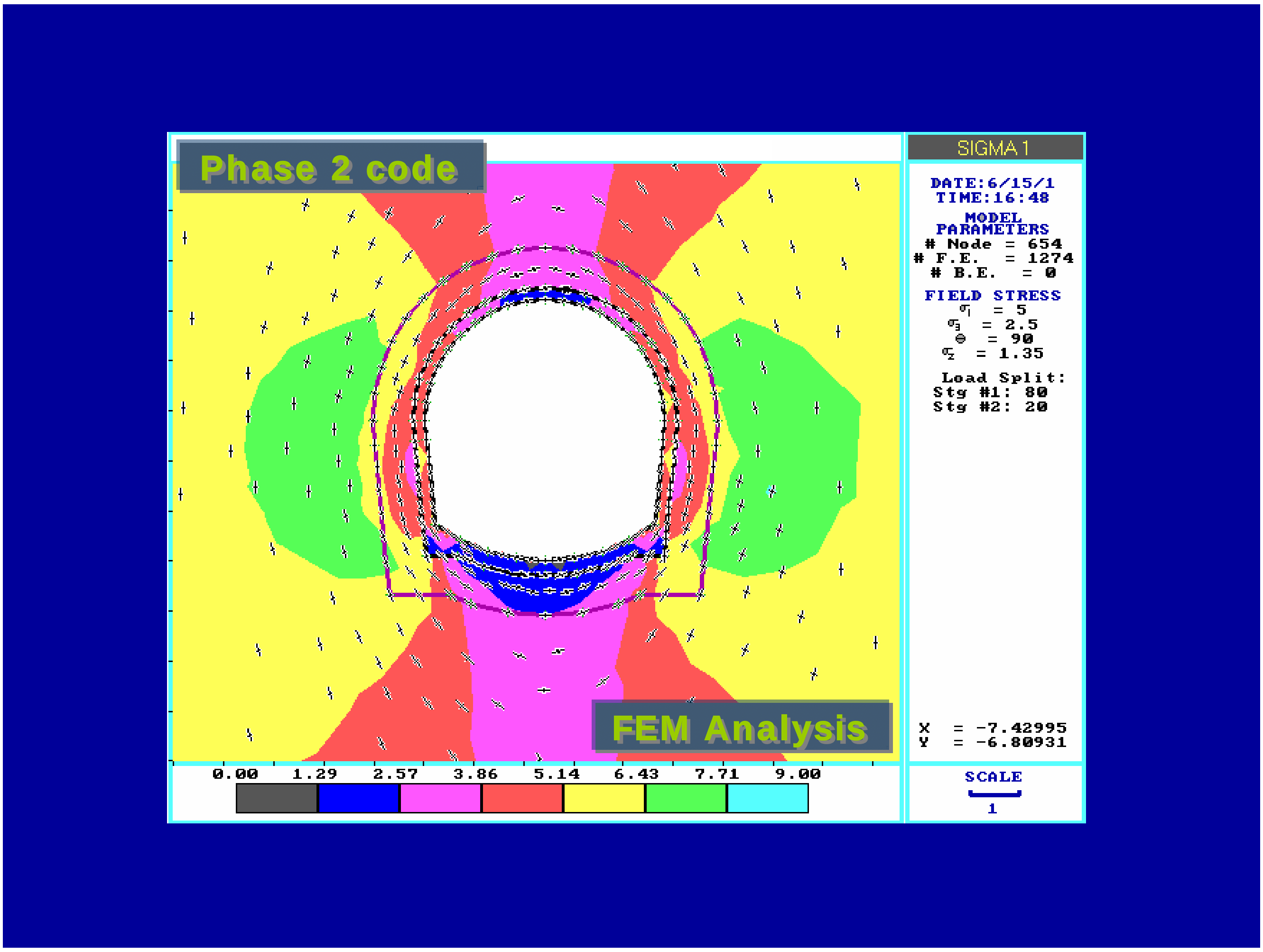
Example
4.75 m
σ_v = 5 MPa
σ_h = 2.5 MPa
RM: Carniole

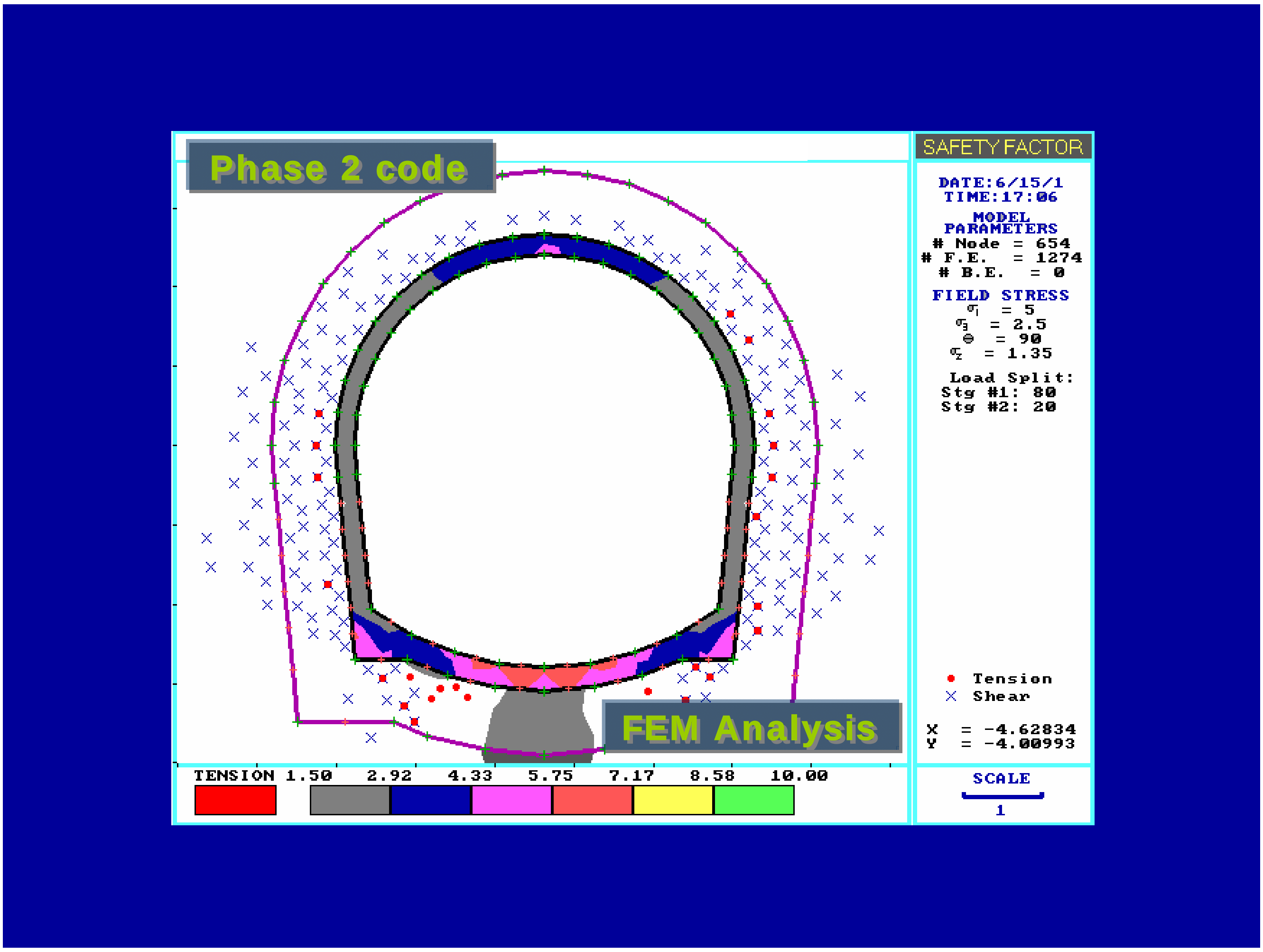


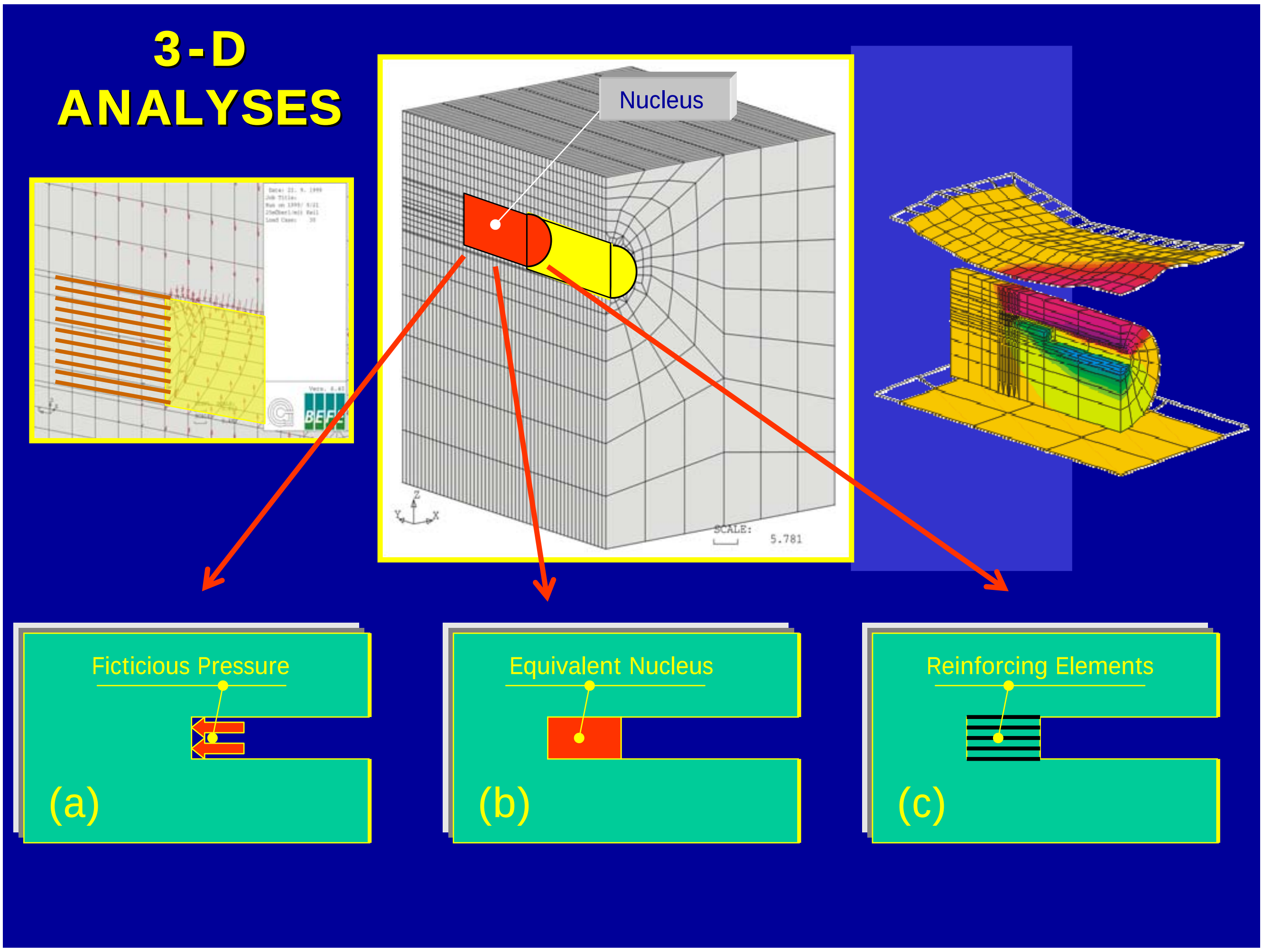
p_i (MPa)
u_r (mm)
0
1
2
3
4
5
6
0
10
20
30
40
p_i sidewall
elastic

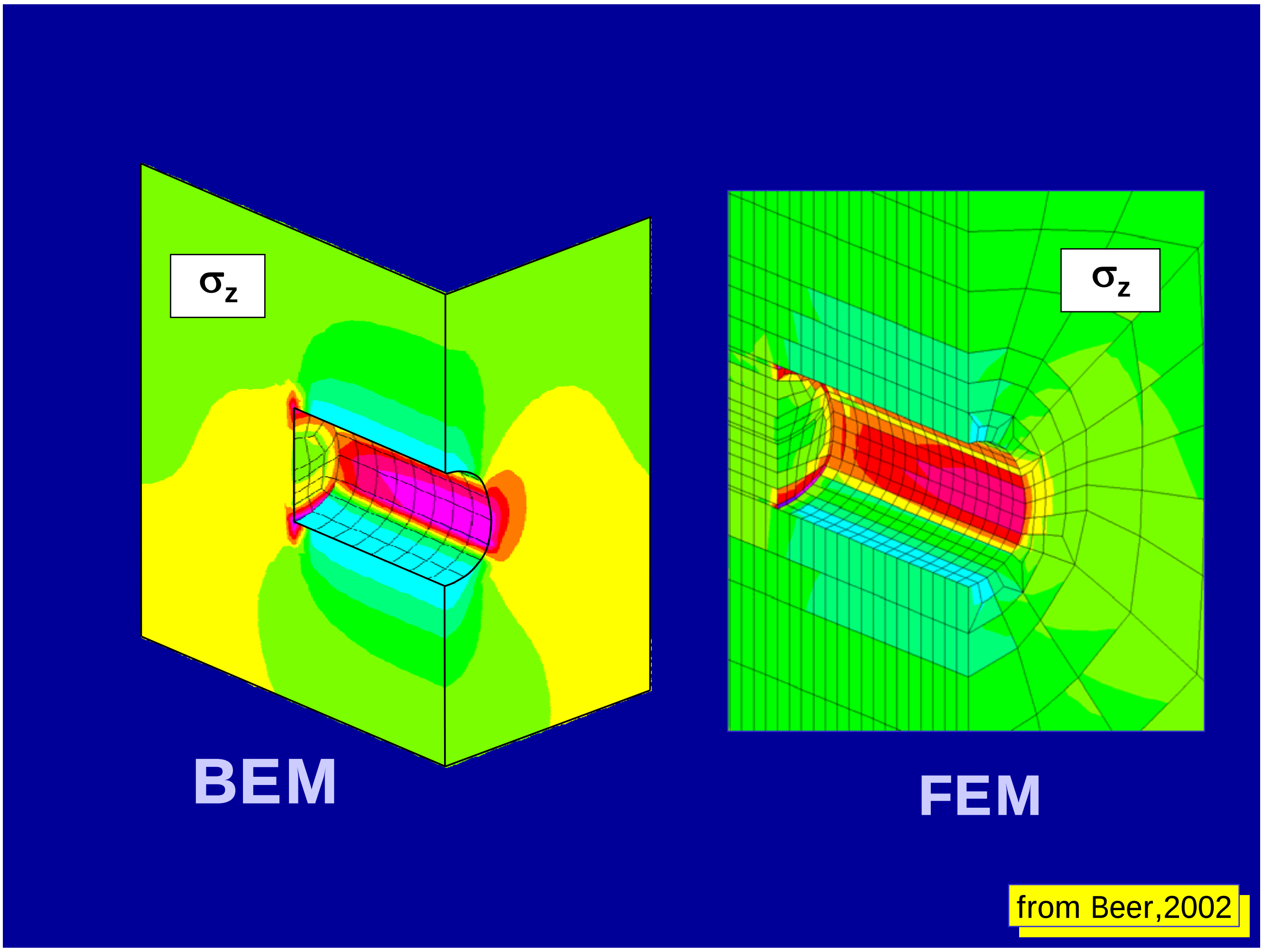


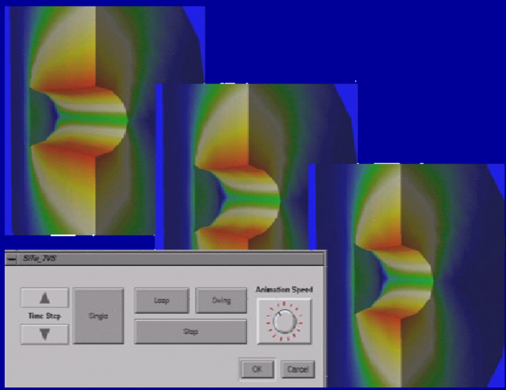
Numerical Methods
“Continuum Modelling”

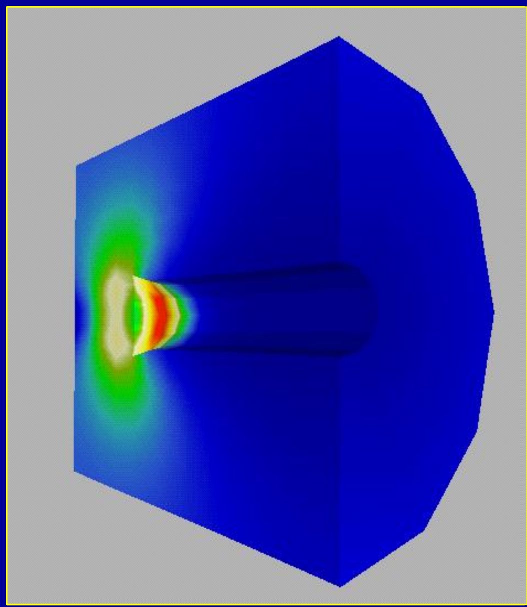

Phase 2 code
SIGMA 1
DATE:6/15/1
TIME:16:48
MODEL PARAMETERS
Node = 654
F.E. = 1274
B.E. = 0
FIELD STRESS
σ1 = 5
σ3 = 2.5
θ = 90
σz = 1.35
Load Split:
Stg #1: 80
Stg #2: 20
FEM Analysis
X = -7.42995
Y = -6.80931
0.00 1.29 2.57 3.86 5.14 6.43 7.71 9.00
SCALE
1


Phase 2 code
SAFETY FACTOR
DATE:6/15/1
TIME:17:06
MODEL PARAMETERS
Node = 654
F.E. = 1274
B.E. = 0
FIELD STRESS
σ1 = 5
σ3 = 2.5
θ = 90
σz = 1.35
Load Split:
Stg #1: 80
Stg #2: 20
Tension
Shear
FEM Analysis
X = -4.62834
Y = -4.00993
TENSION 1.50 2.92 4.33 5.75 7.17 8.58 10.00
SCALE
1


3-D
ANALYSES
Nucleus
SCALE:
5.781
Ficticious Pressure
(a)
Equivalent Nucleus
(b)
Reinforcing Elements
(c)

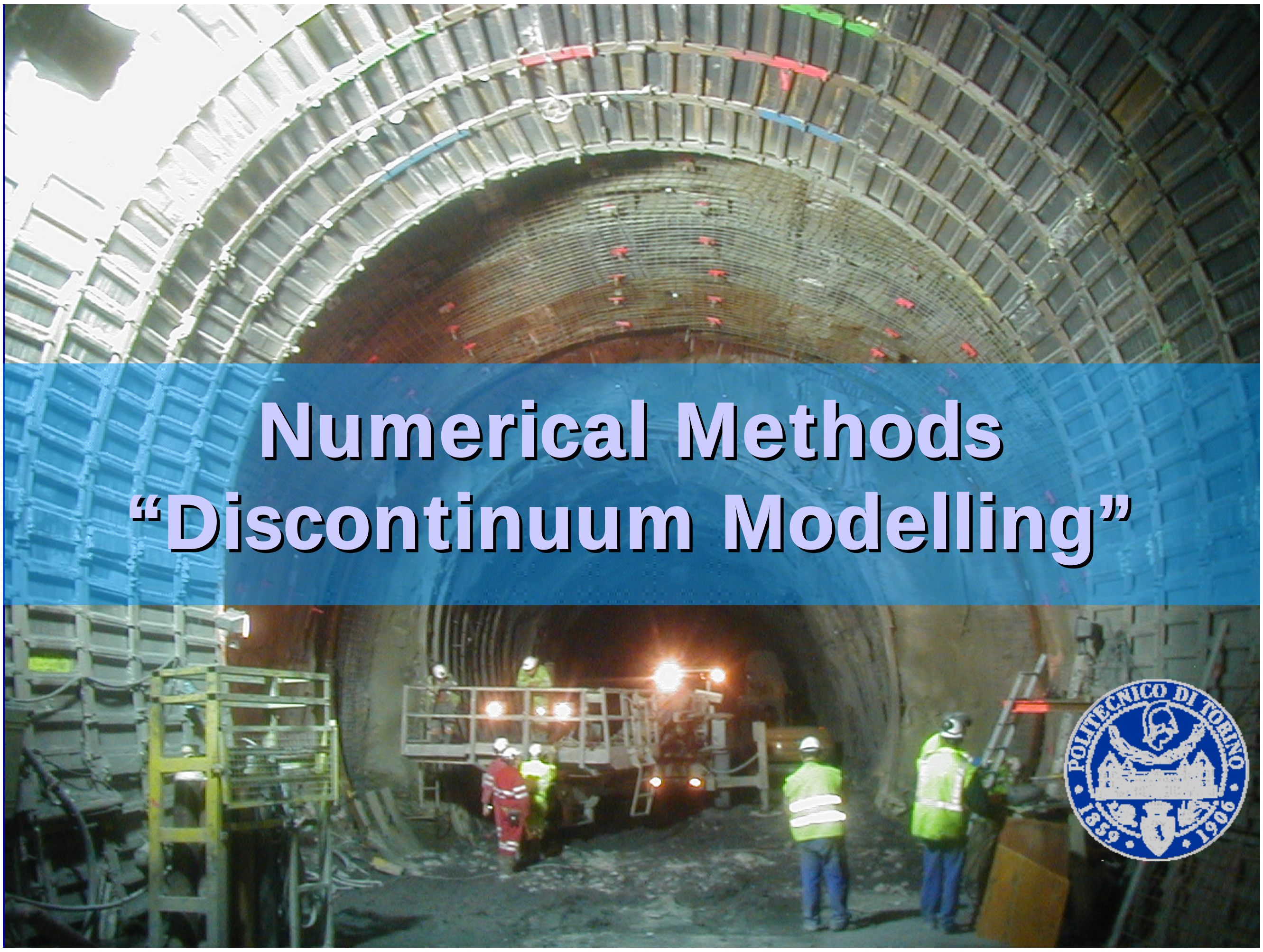

σ_z
σ_z
BEM
FEM
from Beer,2002





Need for visualization of results of modelling

from Beer,2002

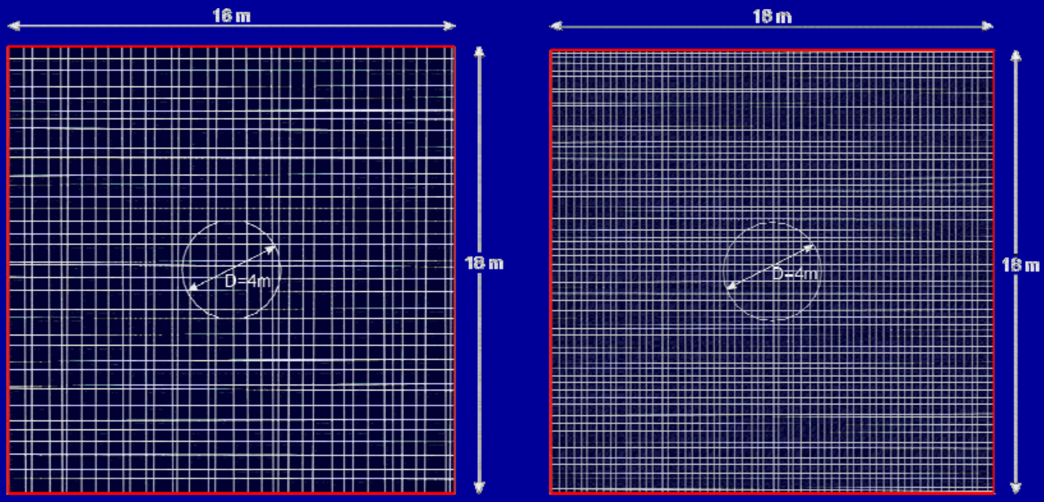


Discontinuum modelling Distinct Element Method –UDEC code

- Circular excavation in a flysch rock mass
- Two models with different joint spacing (respectively 0.5 and 0.3 m)
- Tunnel diameter = 4.00 m
- Two sets of persistent joints (horizontal bedding and vertical jointing)
- Average depth = 350 m

The mechanical properties of blocks and discontinuities have been chosen in order to attain a Q value of:

- *2.0 for first model*
- *1.0 for second model*



Q = 2.0 (poor)   Q = 1.0 (very poor)

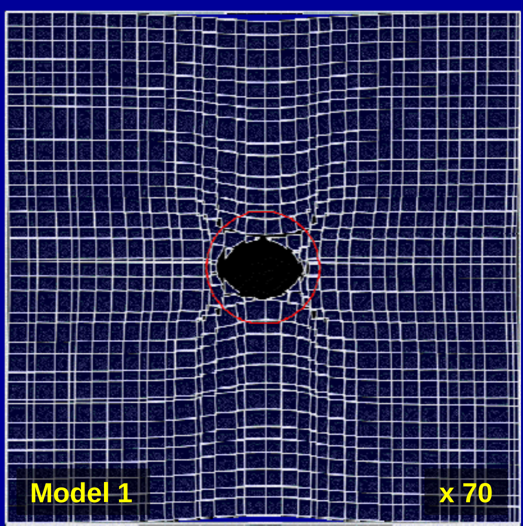
σ_v = 9.45 MPa

σ_h = 4.73 MPa

(Stress ratio K_0 = 0.5)

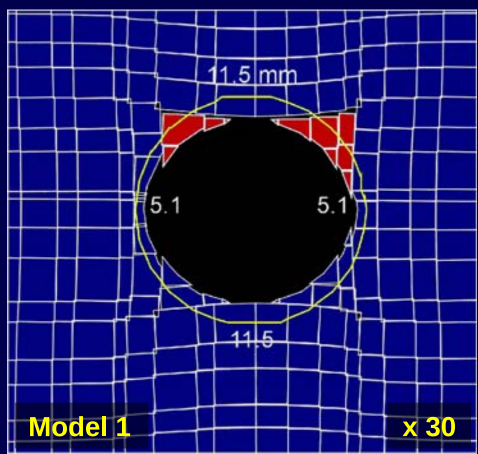
σ_c = 45 MPa

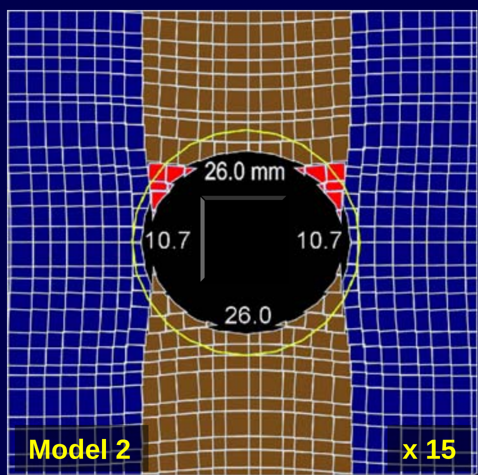
Stability analysis based on numerical approach



Displacements magnified by 70 times

- Instability of roof blocks
- Displacement ranging from 5 to 26 mm
- Displacement increasing as the joint spacing decreases
- Different evolution of displacement field

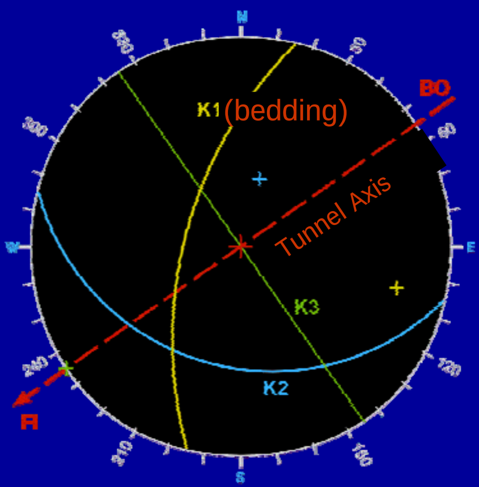


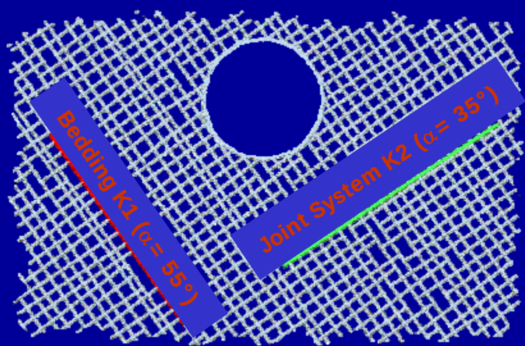


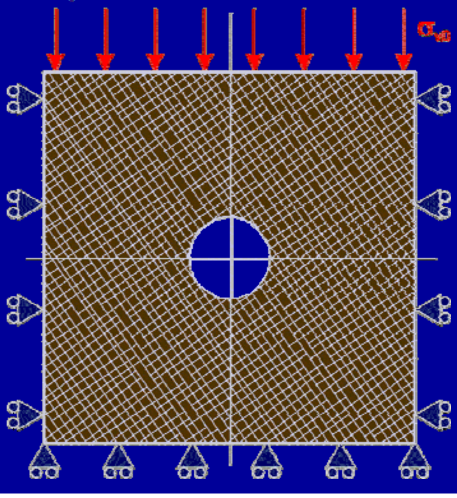
Typical support system behind the cutter head (liner plates, steel mesh, bolting)

Instability at the roof occurs immediately behind the cutter head with the need to install support (liner plates, steel mesh, etc.), with a significant slow-down in progress rate

Instability at the tunnel walls with serious difficulties in positioning the grippers and applying the thrust required

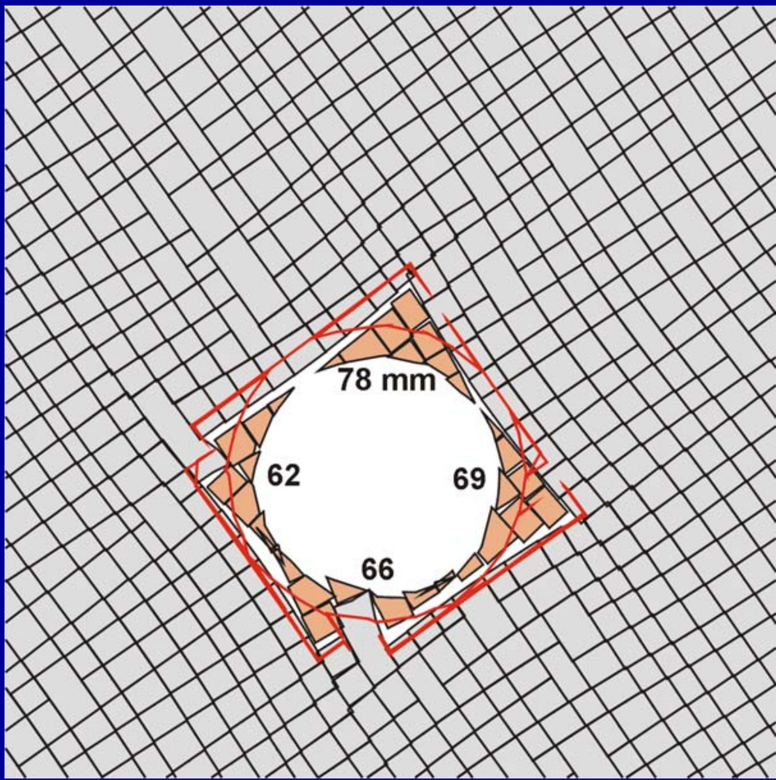






$K_0 = 0.5$
$K_0 = 1.0$
$K_0 = 1.5$

STRESS RATIO

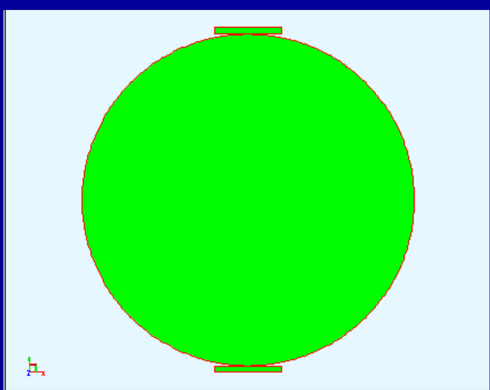


0.5

1.5

Transition from Continuum to Discontinuum (ELFEN code)

ELFEN is a dynamic solver based on the Finite Element Method (FEM) and specialized in problems of transition from continuum to discontinuum. It includes specific Non Linear Fracture Mechanics (NLFM) algorithms to simulate the fracturing and produce discrete fractures



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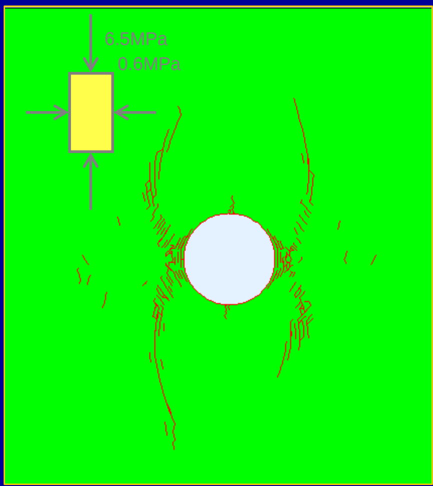

Modelling of problem by ELFEN

Fracturing in the roof of the raise bore pilot hole. Photo courtesy of B. Niederburger, 2001

Tunnels
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Design Analyses
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