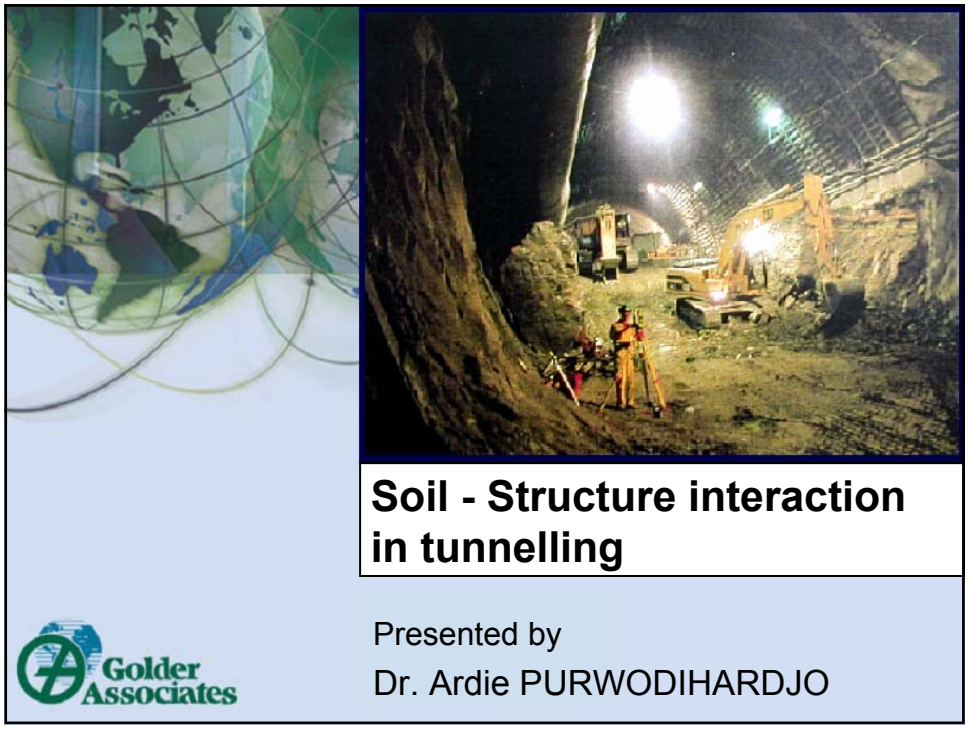

Soil - Structure interaction in tunnelling

Presented by
Dr. Ardie PURWODIHARDJO

Soil - Structure interaction

Two main components :

- Soil
- Structure

DESIGNS → ~~ONE COMPONENT~~ → ~~NOT ECONOMIC OVER CONSEVATIVE~~

Soil - Structure interaction

2

Two main components

- Soil :
  - presence of porewater in soil and its pressures and movement through the soil mass
  - deformation characteristics of the soil skeleton, including its ultimate failure in shear
  - in-situ stresses
  - behaviours of soil
- Structure :
  - magnitude of the relative deflections
  - distribution of forces and stresses within the structures

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3

Tunnels

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Excavation Methods

Drill and Blast Method

Tunnel Boring Machine (TBM)

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Problems in tunnelling

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CONTROL DEFORMATIONS

The need for control of deformations arises from the following concerns:

- To avoid damage to the infrastructure and buildings on the surface.
- To ensure the safety of the workmen in various stages of the excavation.
- To control the increasing of the bending moments in the temporary lining that may result from loosening of the ground, asymmetric loading (due to the geomorphology, proximity to another cavity), and heterogeneity of the ground.
- To avoid the initiation or recurrence of the phenomenon of slope stability.

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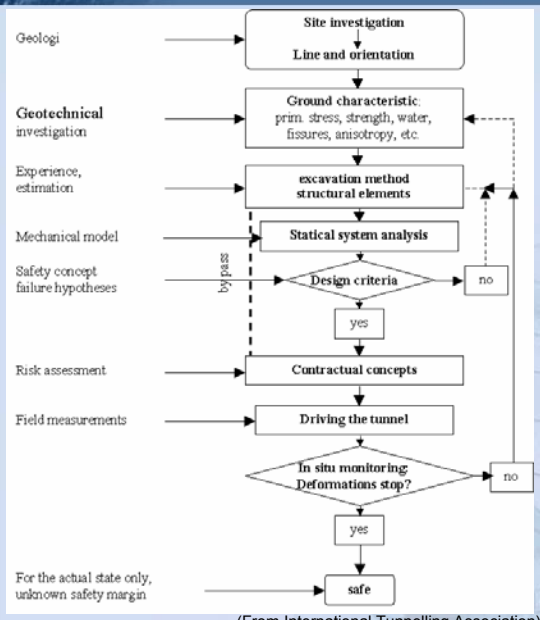
DESIGN PROCEDURE IN TUNNELLING



(From International Tunnelling Association)

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METHOD OF SOIL-STRUCTURE ANALYSIS

- Closed from solutions/ Analytical methods
- Numerical methods :
  - method of springs
  - finite element method

9

FINITE ELEMENT METHODS

DATA NEEDED :

- Geotechnical data
  - Mechanical behaviour of ground
  - Mechanical properties of ground
  - Initial state of stress
  - Model boundary conditions
- Lining data
  - Mechanical behaviour of lining
  - Mechanical properties of lining
- Support/ground interface data
- Mesh generation and computations

10

MECHANICAL BEHAVIOUR OF GROUND

CONSTITUTIVE MODEL

DEFORMATION ⟷ STRESS

BEHAVIOURS OF GROUND

- Elastic
- Elasto-plastic
- Softening-hardening
- Creep : Viscoelastic and viscoplastic
- Swelling, etc…

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MECHANICAL PROPERTIES OF GROUND

ELASTIC MODEL :

- **Young's modulus : E**
- **Poisson ratio : υ**

TRESCA MODEL :

- **Undrained cohesion : Cu**

Mohr Coulomb MODEL :

- **Cohesion : C**
- **Internal friction angle : Ø**
- **Dilation angle : ψ**

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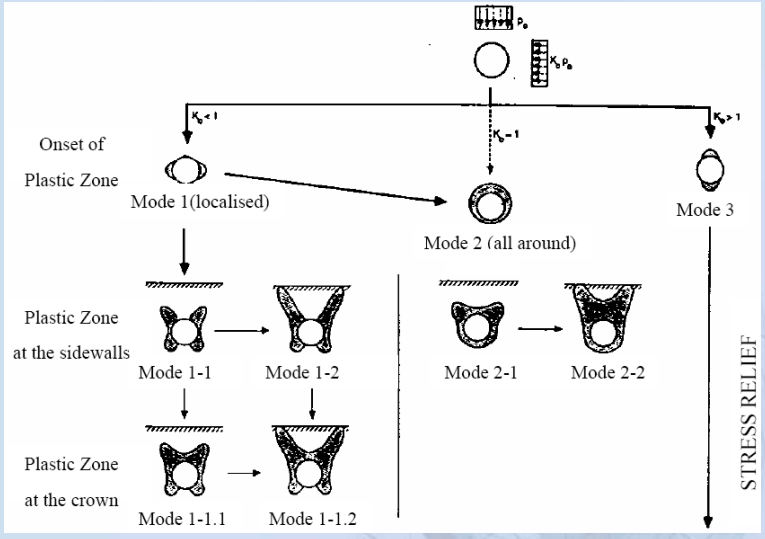
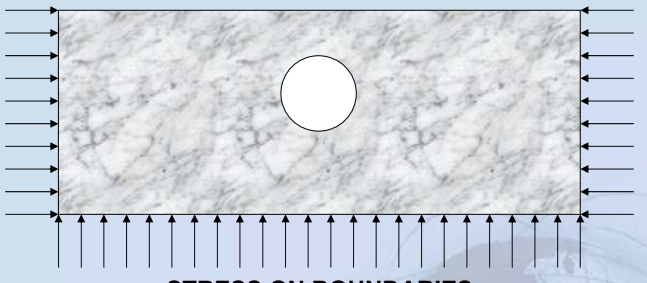
INITIAL STATE OF STRESS

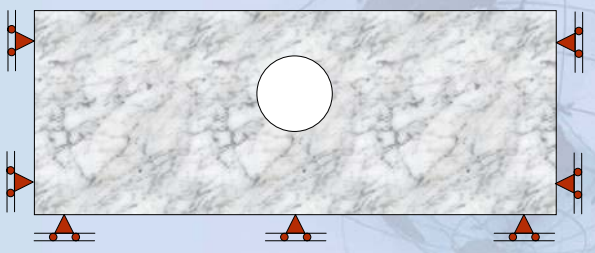


Onset of Plastic Zone around a tunnel in urban environment for different Ko values and as stress relief takes place around it (the ground is ideally plastic and c=0 and φ is 35° (Wong and Kaiser,1991)

MODEL BOUNDARY CONDITION



STRESS ON BOUNDARIES



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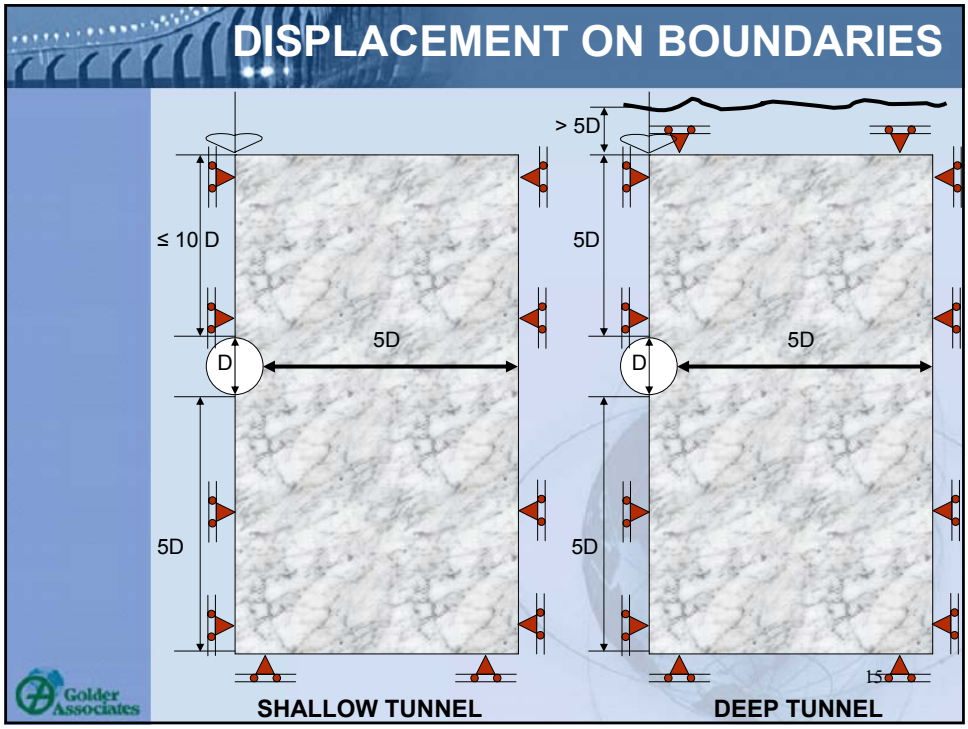
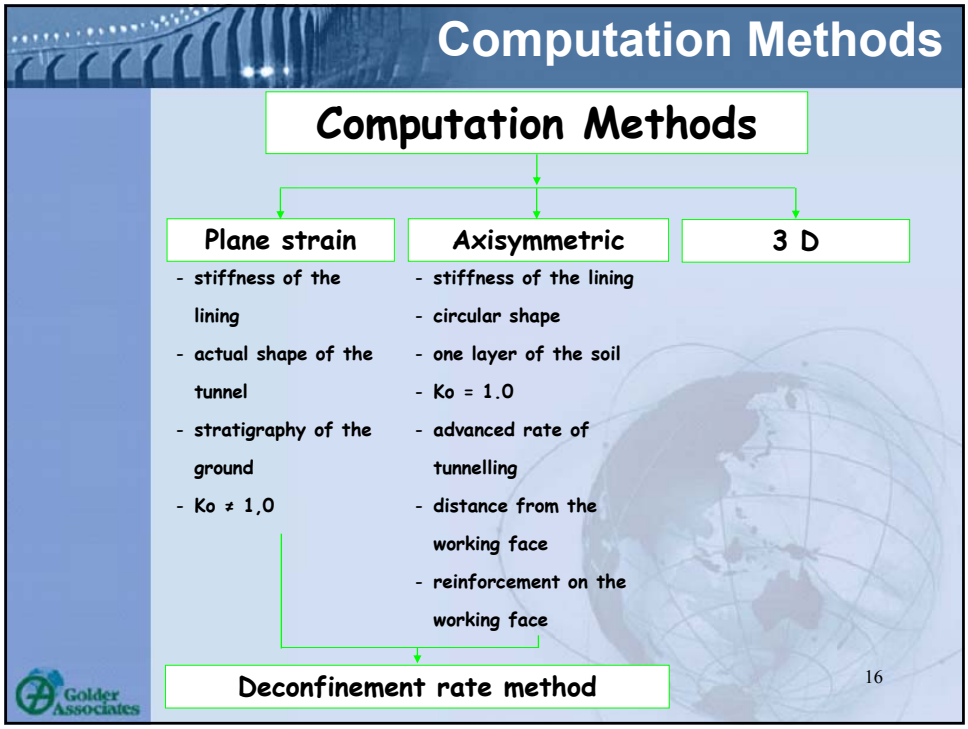
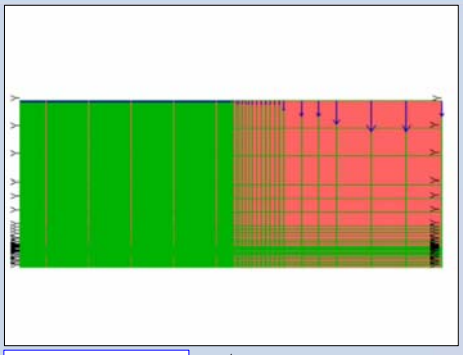
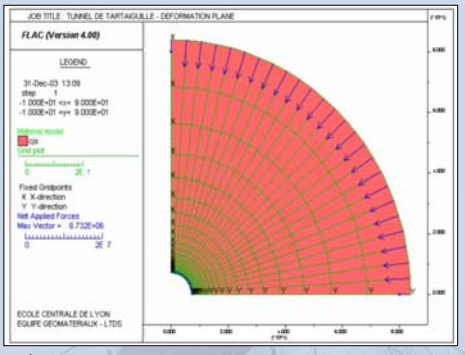
DISPLACEMENT ON BOUNDARIES


DISPLACEMENT ON BOUNDARIES
> 5D
≤ 10 D
5D
D
5D
5D
5D
D
5D
SHALLOW TUNNEL
DEEP TUNNEL


Computation Methods
Computation Methods
Plane strain
- stiffness of the lining
- actual shape of the tunnel
- stratigraphy of the ground
- Ko ≠ 1,0
Axisymmetric
- stiffness of the lining
- circular shape
- one layer of the soil
- Ko = 1.0
- advanced rate of tunnelling
- distance from the working face
- reinforcement on the working face
3 D
Deconfinement rate method
16

Calculation Procedure

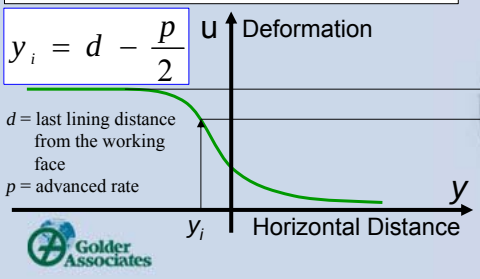


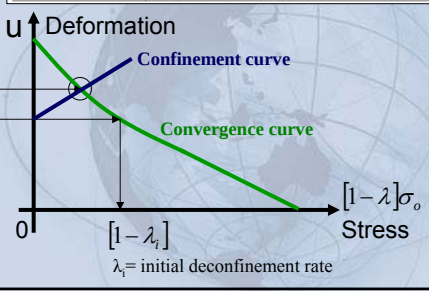


$$y_i = d - \frac{p}{2}$$

d = last lining distance from the working face

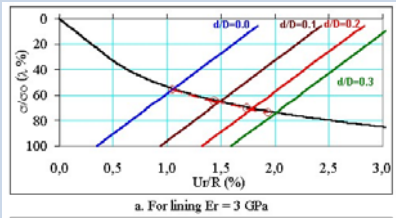
p = advanced rate



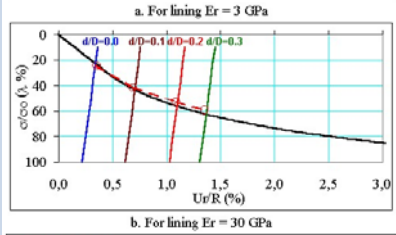


λ_i= initial deconfinement rate

Convergence – Confinement Methods

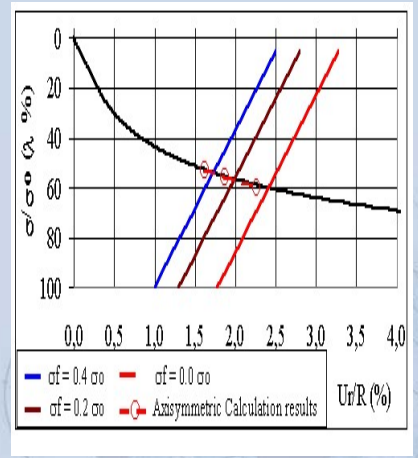


a. For lining Er = 3 GPa

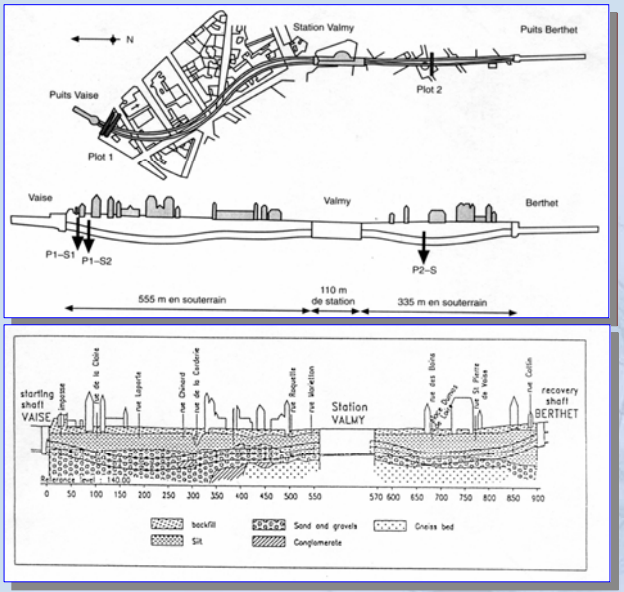


b. For lining Er = 30 GPa

Axisymmetric calculation results



Worksite of Lyon Metro line D



OBJECTIVE

To assess the influence of

strain-softening of the soils on settlement

due to tunnelling

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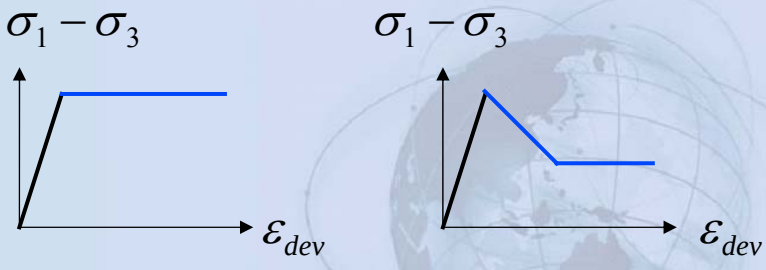
CONSTITUTIVE MODEL USED

- Mohr-Coulomb
- **Mohr-Coulomb**

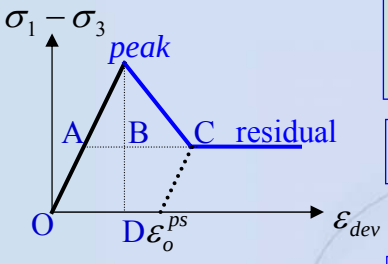
with strain-softening behaviour



21

MOHR-COULOMB WITH STRAIN-SOFTENING BEHAVIOUR

(PURWODIHARDJO AND CAMBOU 1999)



Two additional parameters
- *parameter* χ
- *parameter* s

$$BC = \chi \cdot AB$$

$$\sigma_{res} = s \cdot \sigma_{peak}$$

22

GENERAL EQUATIONS

$$\text{for } \varepsilon^{ps} = 0 \begin{cases} c = c^{peak} \\ \tan\phi = \tan\phi^{peak} \\ \sigma^{t} = \sigma^{t\,peak} \end{cases}$$

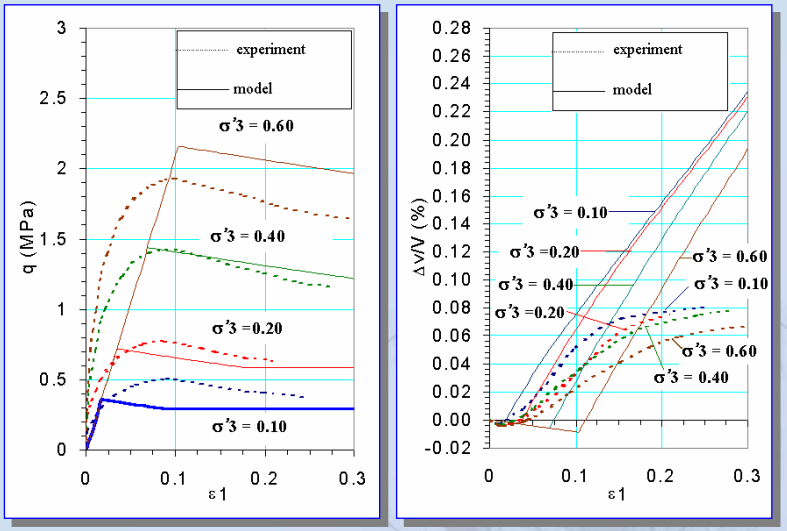
$$\text{for } 0 < \varepsilon^{ps} \le \varepsilon_0^{ps} \begin{cases} c = \left(1-(1-s)\dfrac{\varepsilon^{ps}}{\varepsilon_0^{ps}}\right)\cdot c^{peak} \\ \tan\phi = \left(1-(1-s)\dfrac{\varepsilon^{ps}}{\varepsilon_0^{ps}}\right)\tan\phi^{peak} \\ \sigma^{t} = \left(\dfrac{\varepsilon^{ps}}{\varepsilon_0^{ps}}\right)\sigma^{t\,peak} \end{cases}$$

$$\text{for } \varepsilon^{ps} > \varepsilon_0^{ps} \begin{cases} c^{res} = s\cdot c^{peak} \\ \tan\phi^{res} = s\cdot\tan\phi^{peak} \\ \sigma^{t\,res} = 0 \end{cases}$$

23

VALIDATION TEST ON DENSE SANDS

(MOHKAM, 1983)



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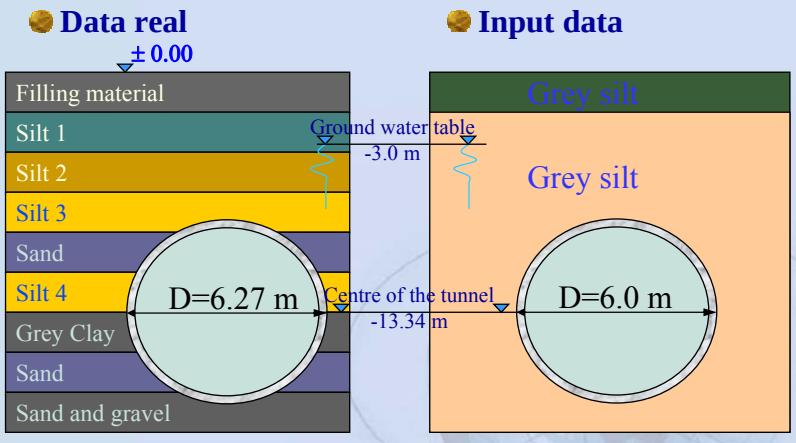
STRATIGRAPHY ON SECTION P2



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PARAMETERS OF SOILS AND LININGS

Soils

Five parameters of Mohr-Coulomb :

E_s = 6.0 Mpa
ν = 1/3
c = 50 kPa
ϕ = 22°
Ψ = 2°

Two parameters of strain-softening model :

Model I : χ = 5.0
s = 0.5, 0.75 et 1.0

Linings

Thickness of lining : 350 mm

Elastic parameters :

E_c = 13.5 Gpa
ν_c = 0.20

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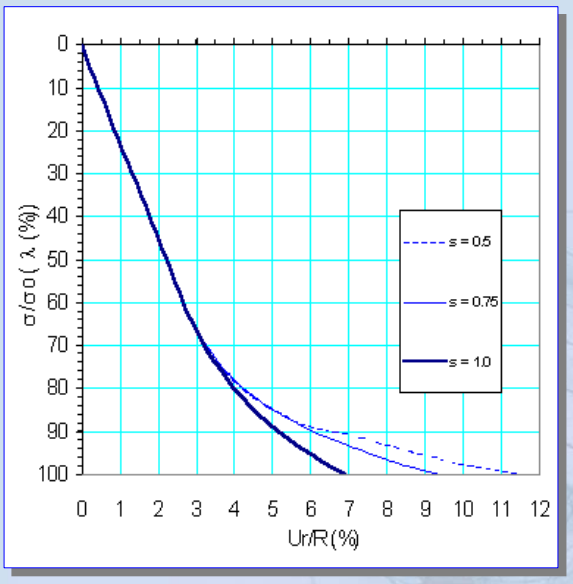
CHARACTERISTIC CURVES OF SOIL
(PLANE STRAIN CALCULATION)



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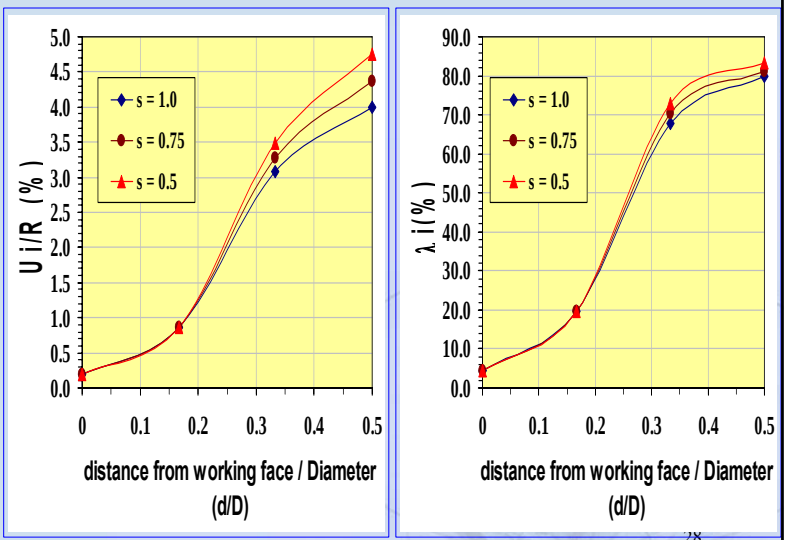
INITIAL DEFORMATIONS AND DECONFINEMENT RATE
(AXISYMETRIC AND PLANE STRAIN CALCULATIONS)



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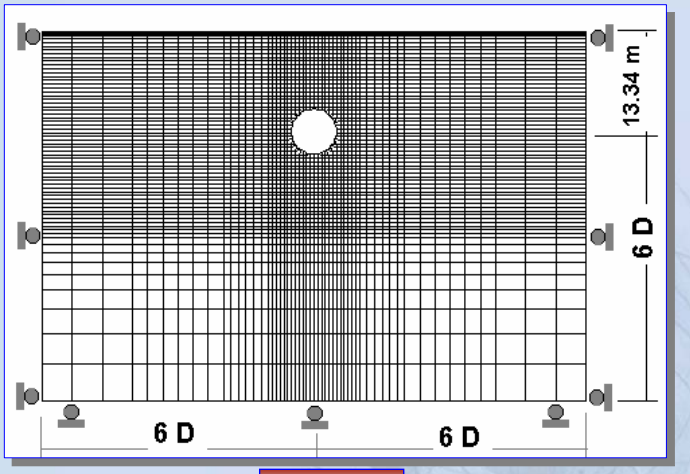
PLANE STRAIN CALCULATION

Mesh and Boundary condition used



Ko =0.5

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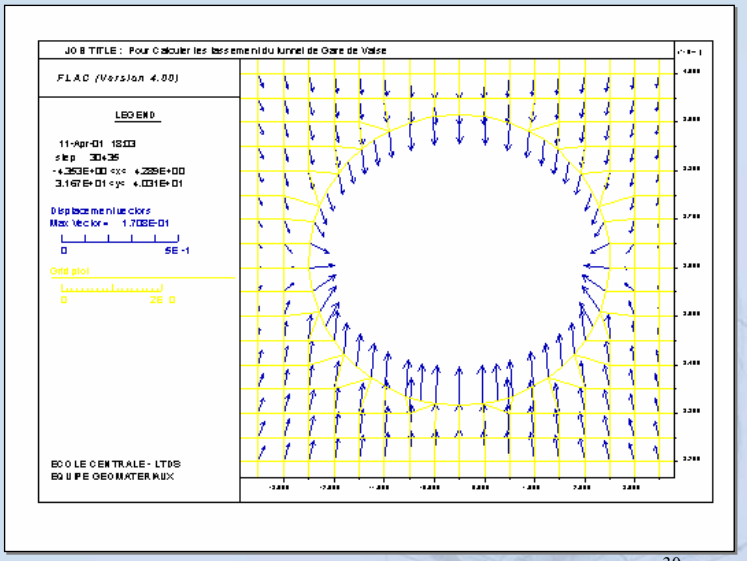
DEFORMATION AT VICINITY OF TUNNEL



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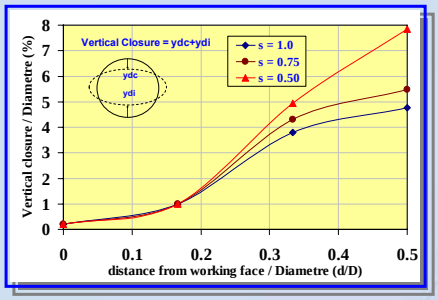
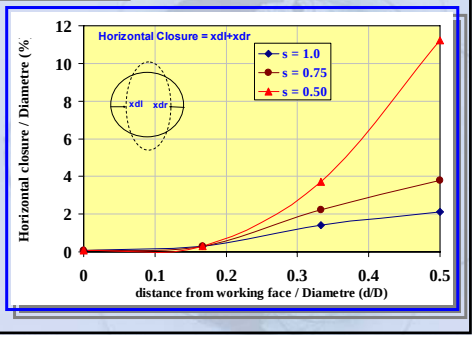
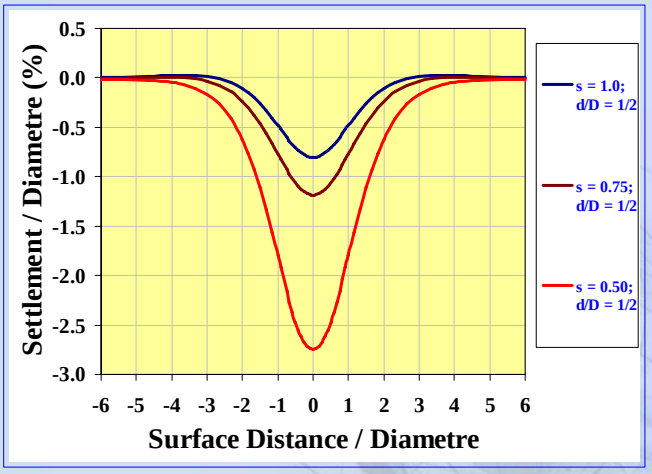
VERTICAL AND HORIZONTAL CLOSURES





SETTLEMENTS ON GROUND SURFACE



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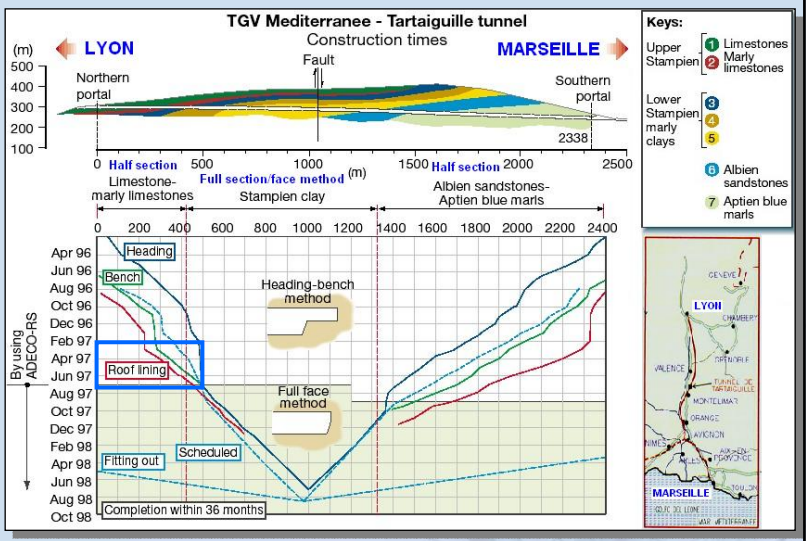
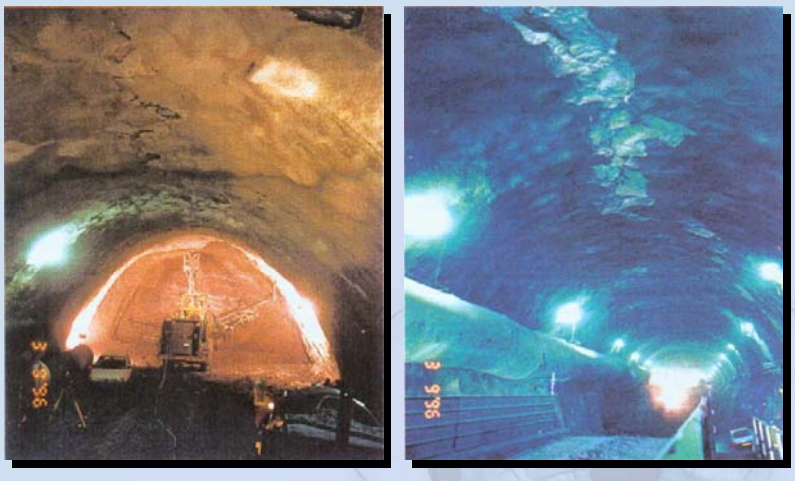
Tunnel of Tartaiguille



33

Cracking at the crown



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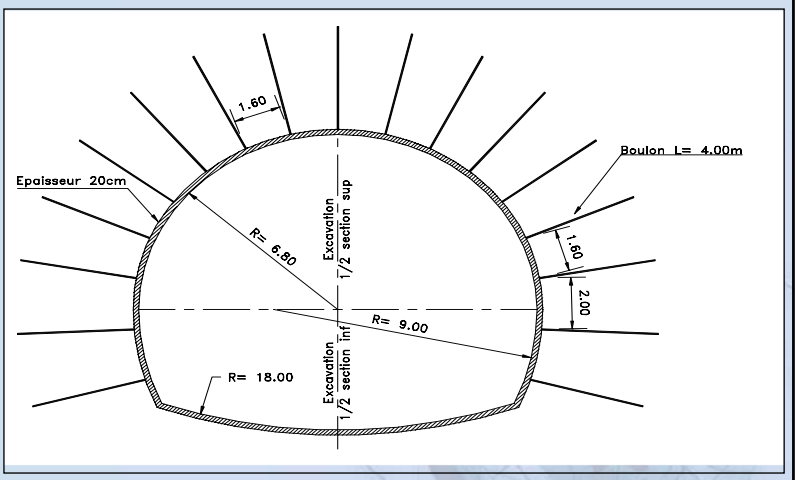
Cross section of tunnel

Heading – Bench method



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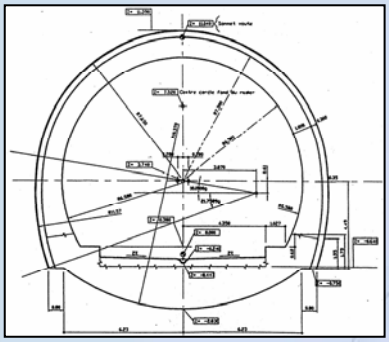
Cross section of tunnel

Full face method



Dimensions of tunnel

Soil stratigraphy at section PM 1168

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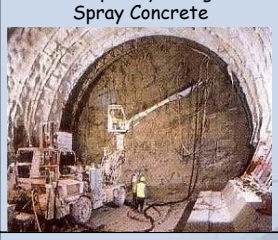
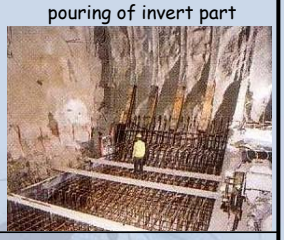
Excavation Sequence – Full face method

PHASE I
Reinforcement of working face

PHASE III
Temporary Lining
Spray Concrete



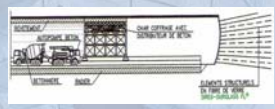
PHASE IV
Excavation and
pouring of invert part



PHASE II
Excavation in full section/face

Temporary Lining
Steel frame - HEB 300

PHASE V
Final Lining
Cast-in-situ concrete



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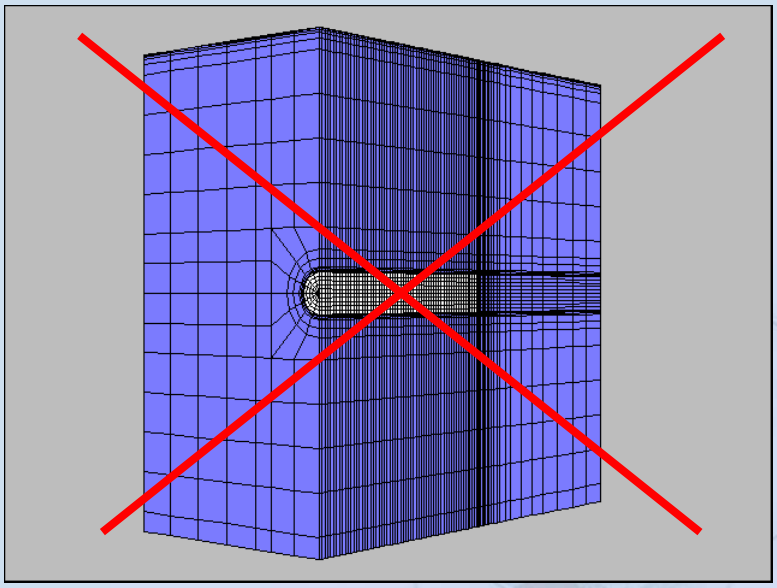
3 Dimensional Model

- Title
- Introduction
- Comput. Methods
- Example Cases
  - Tartaiguille
  - Lakhdaria
  - G-Freezing
- Notes
- Q & A



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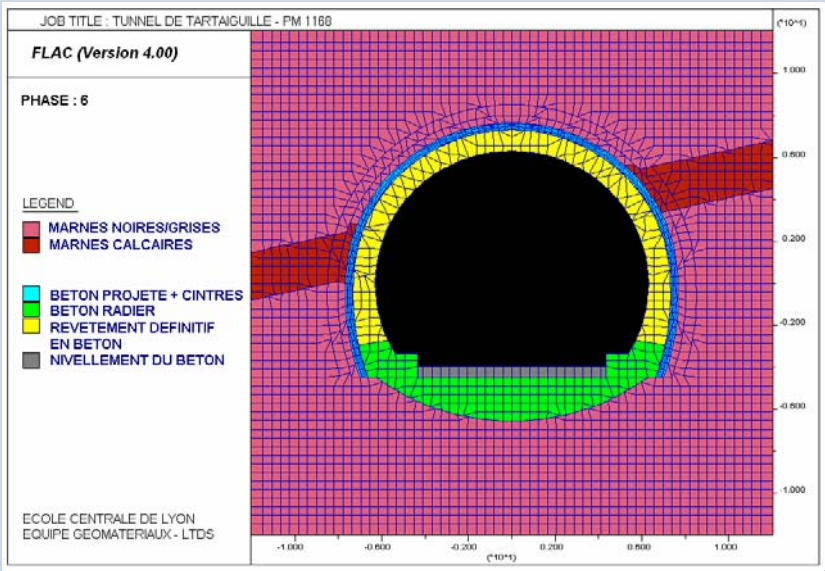
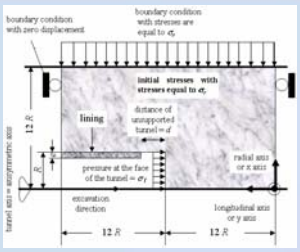
Plane Strain Model

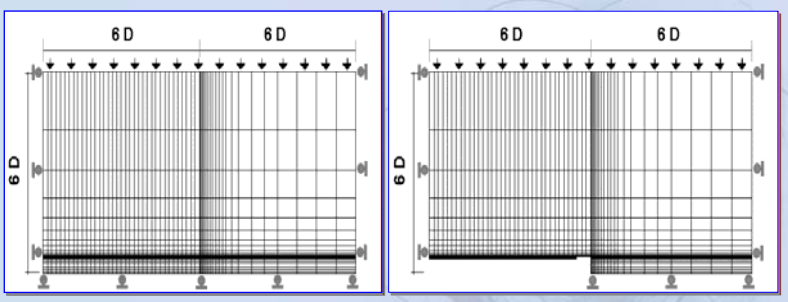


Axisymmetric model

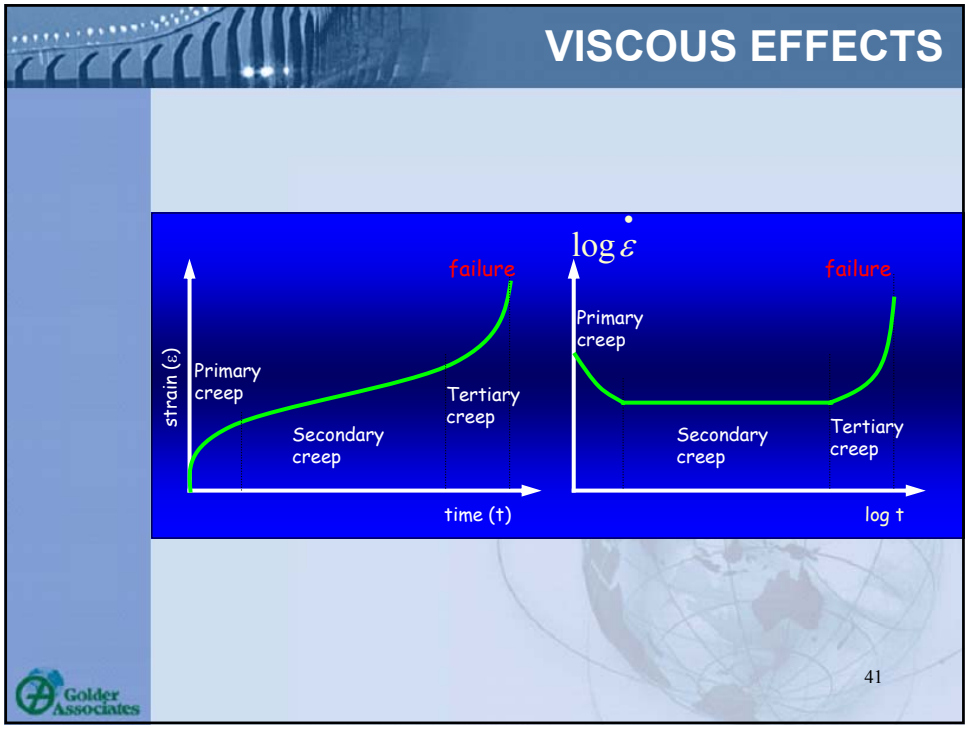


Equivalent pressures (Peila, 1994)

$$\sigma_f = \min\left(\frac{n.T_b}{S}; \frac{n.S_b}{S}\right)$$



Initial mesh → Sequential excavation method (SEM) → Final mesh


VISCOUS EFFECTS
strain (ε)
Primary creep
Secondary creep
Tertiary creep
failure
time (t)
log ε̇
Primary creep
Secondary creep
Tertiary creep
failure
log t
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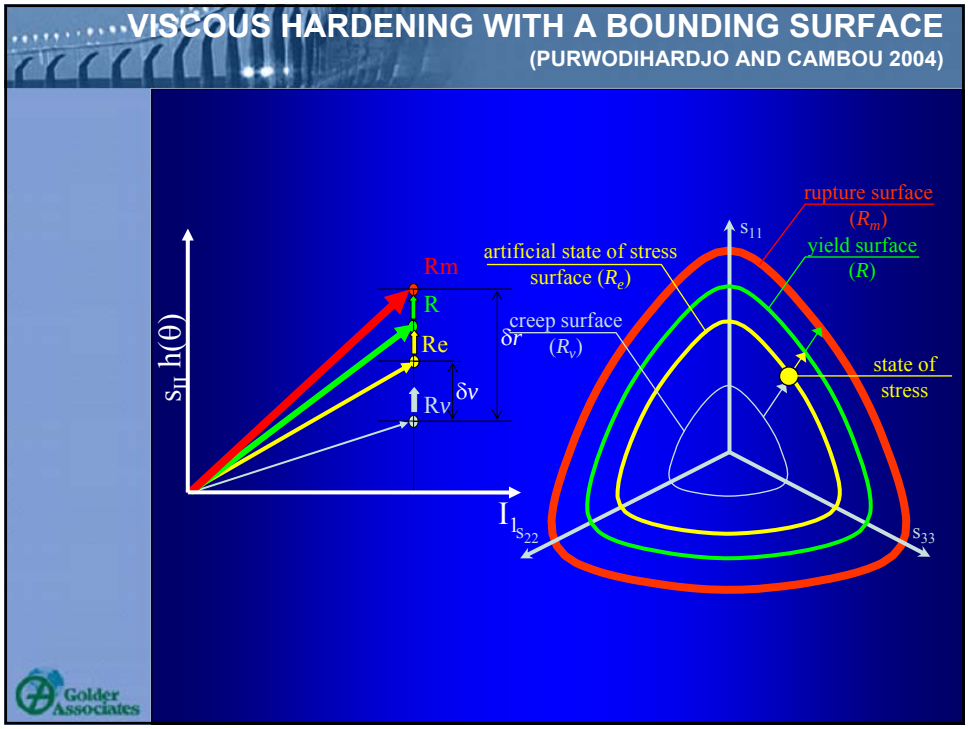
VISCOUS HARDENING WITH A BOUNDING SURFACE
(PURWODIHARDJO AND CAMBOU 2004)
s_II h(θ)
Rm
R
Re
Rv
δv
δr
artificial state of stress surface (Re)
creep surface (Rv)
rupture surface (Rm)
yield surface (R)
state of stress
s11
s22
s33
I1
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Deviatoric viscous mechanism

Viscoplastic strain rate

$$\dot{\varepsilon}_{ij}^{vd} = \frac{1}{\eta}\left(\frac{\delta v}{\delta r}\right)^{m} G_{ij}^{vd}$$

Viscosity

$$\eta = \eta_0\left(1-\left(\frac{R_e}{R_m}\right)^2\right)^k$$

Function of retardation

$$\left(\frac{\delta v}{\delta r}\right)^{m} = \left(\frac{R_e - R_v}{R_m - R_v}\right)^{m}$$

Direction

$$G_{ij}^{vd} = \frac{\partial f^e}{\partial \sigma_{ij}} - \left(\frac{\partial f^e}{\partial \sigma_{kl}} n_{kl}\right) n_{ij}$$

where

$$m = m_1 + m_2 \frac{R_e}{R_m}$$

where

$$R_v = R_e\left(1 - \frac{1}{\exp\left(A^v \frac{R_m}{R_e} e_{II}^{vd}\right)}\right)$$

→ Evolution of creep surface

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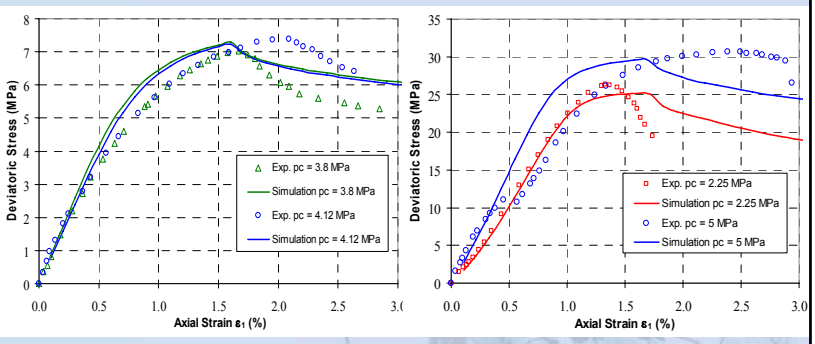
SIMULATION RESULTS OF TRIAXIAL TESTS

Black marl **Calcareous marl**



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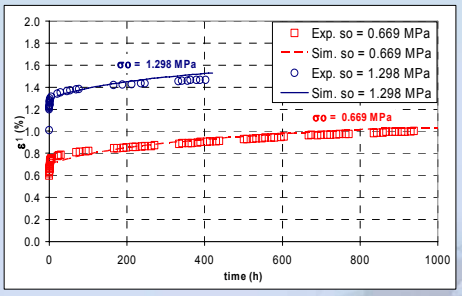
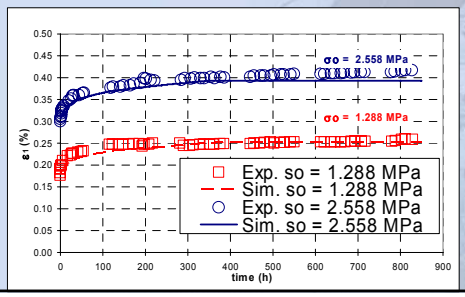
SIMULATION RESULTS OF CREEP TESTS

Black marl



Calcareous marl



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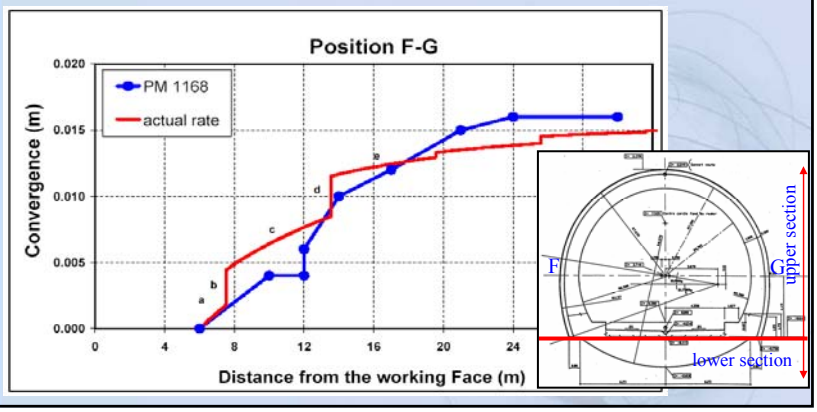
Axisymmetric condition with ELASTOPLASTIC-VISCOPLASTIC model (Purwodihardjo, 2004)

The sequences of the actual excavation are as follows:

(a) excavating the section with the advance rate: 1.5 m per 0.5 day until 6 m,
(b) stopping for one day
(c) continuing the excavation with the advance rate: 1.5 m per 0.5 day until 6 m,
(d) stopping for three days (to represent the installation time of the anchors on the working face)
(e) Continuing the excavation.



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Lakhdaria Tunnel – Algeria
(Autoroute Est-Ouest)




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Lakhdaria Tunnel - Algeria


Jet Grouting in T2 East

Reinforcement of working face

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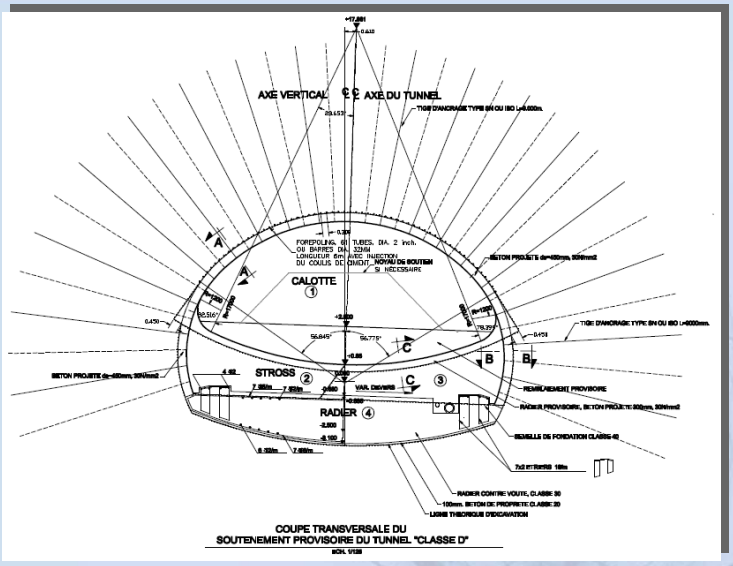
Lakhdaria Tunnel - Algeria



Cross section of tunnel

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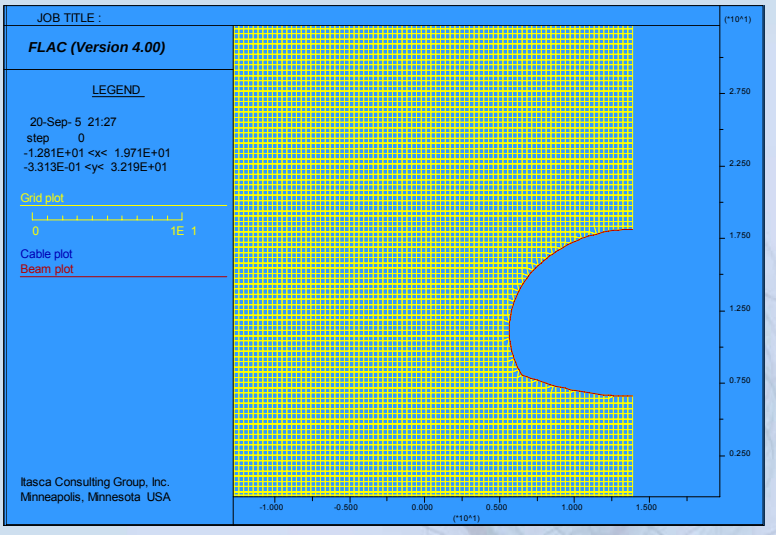
Lakhdaria Tunnel Algeria



GRID MESH USED

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Ground Freezing

Phase Changes

LIQUID → SOLID → LIQUID

Structures supported by ground → Ground supported by structures

GROUND PROPERTIES = *f* (temperature, time)

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Ground Freezing

ADVANTAGES

1.STRENGTH
Soil strength is increased many times and frequently excavations are rendered stable without any further temporary support. Frozen soil can be likened to a weak concrete or rock therefore complete stability can be assured.

2.IMPERMEABILITY
Impermeability is common to all frozen soil types thus the requirement for dewatering or pumping is eliminated.

3.STABILITY
Settlement associated with vibration during piling and removal of fines due to pumping are eliminated.

4.NON-POLLUTING
Freezing does not pollute the ground water or affect its level in any way.

5.VERSATILITY
Freezing satisfactorily stabilises and excludes ground water in all types of ground from fine micro-grain to fissured rock structures.

6.SAFETY
A safe working environment is provided eliminating hazards associated with toxic chemicals compressed air working excessive noise and the possibility of pumping contaminated groundwater.

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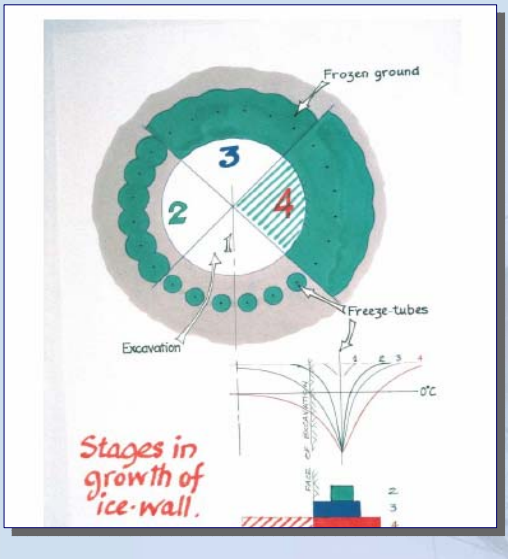
Ground Freezing



- Install the freeze tubes around the tunnel
- Development of the ice ring
- Design thickness achieved
- Complete Freezing of Core

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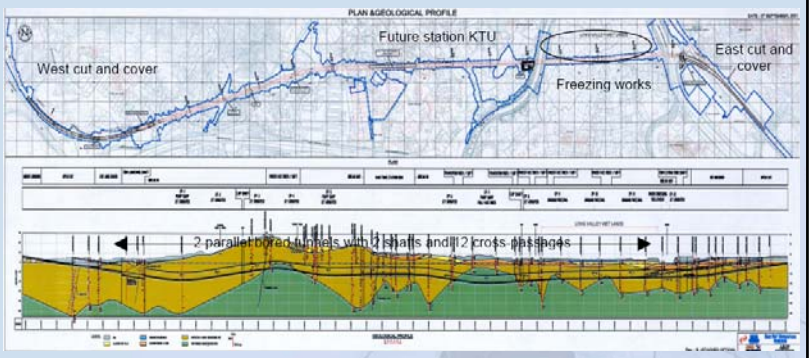
Lok Ma Chau Spur Line, Hong Kong



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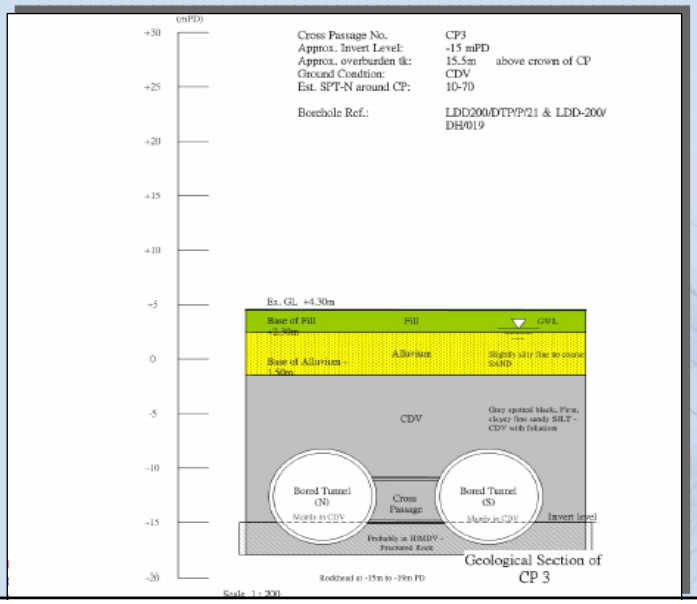
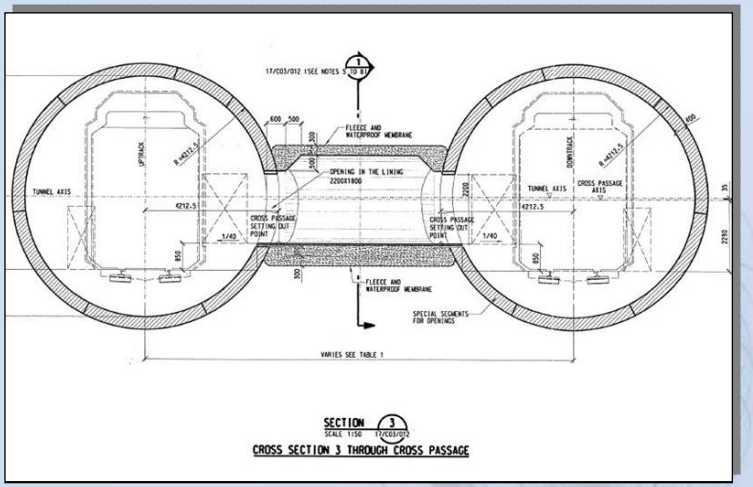
Lok Ma Chau Spur Line, Hong Kong

Ground conditions



Lok Ma Chau Spur Line, Hong Kong

General arrangement of cross passages



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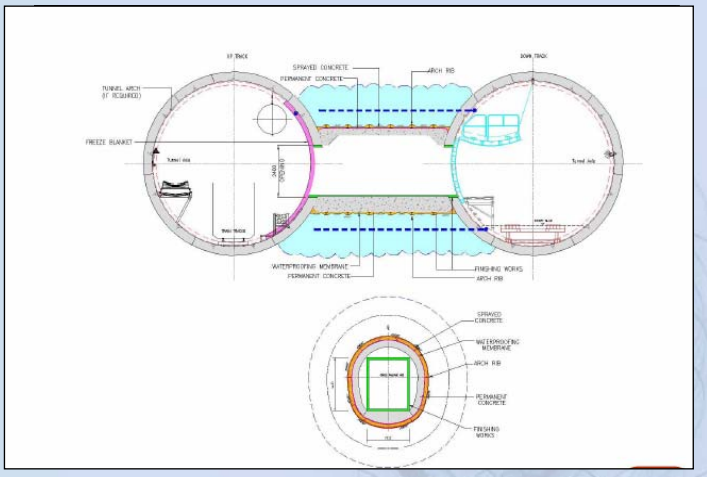
Lok Ma Chau Spur Line, Hong Kong

Construction Sequence



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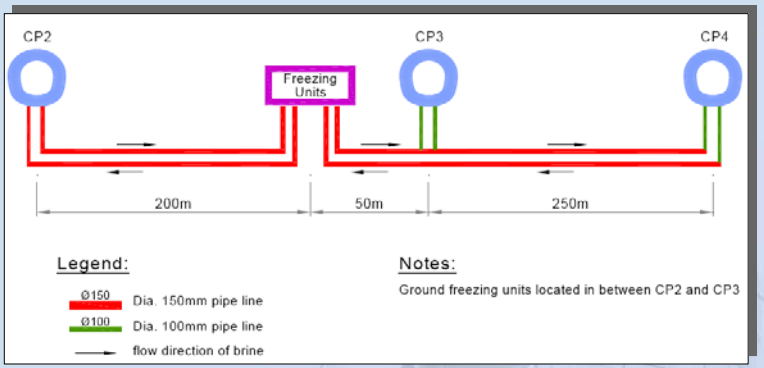
LDB201 Ground Freezing
Site Installation – Freeze Unit (Down)



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LDB201 Ground Freezing
Site Installation – Freeze Unit (Down)

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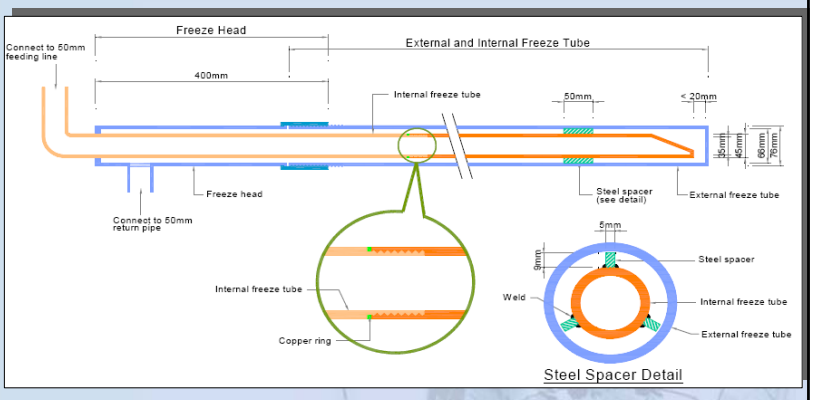
LDB201 Ground Freezing
Site Installation – Freeze Probe Details



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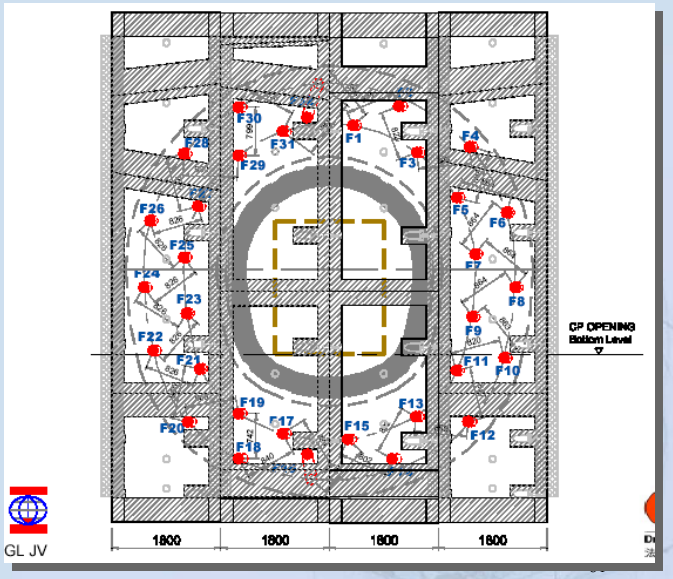
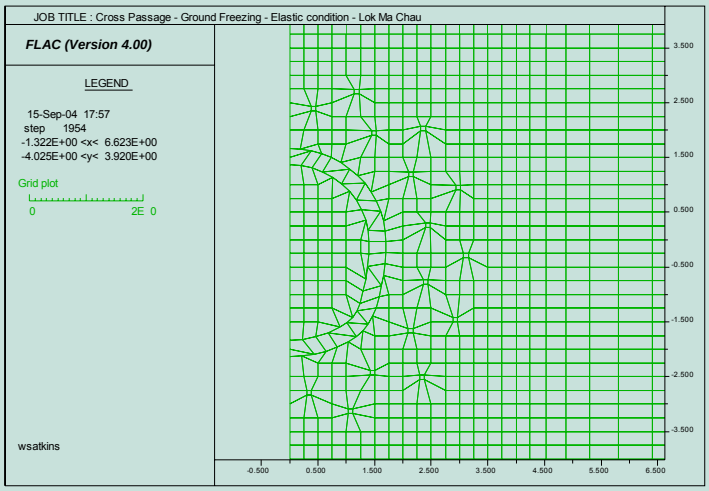
Ground Freezing

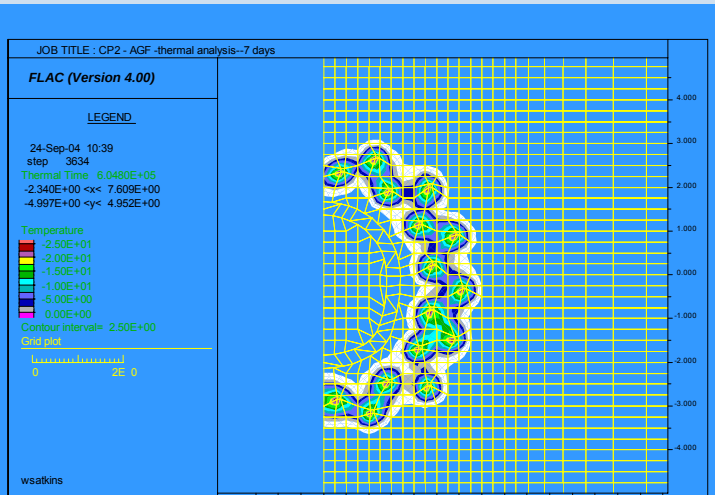


Ground Freezing

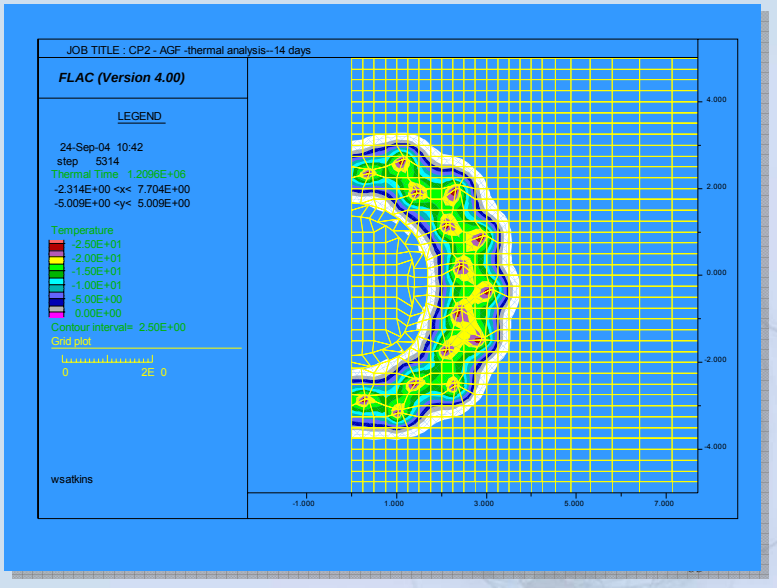
Ground Freezing



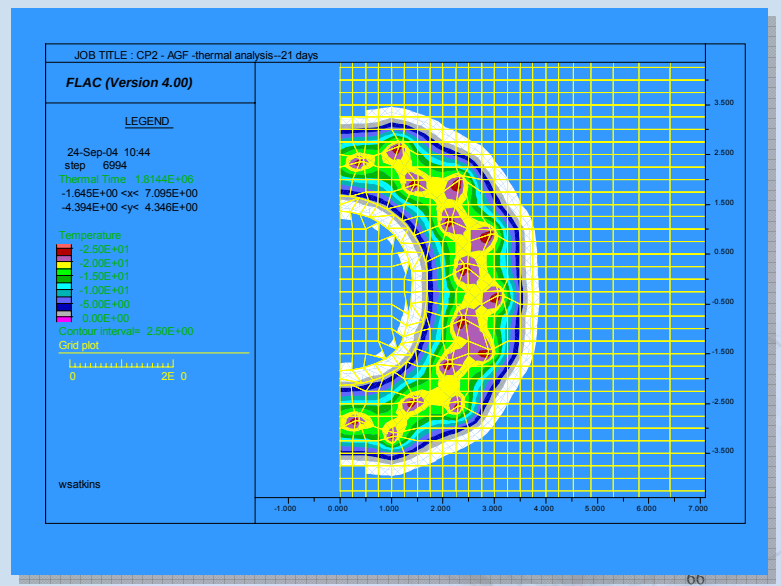
Ground Freezing - Temp. Contours at 1 Week



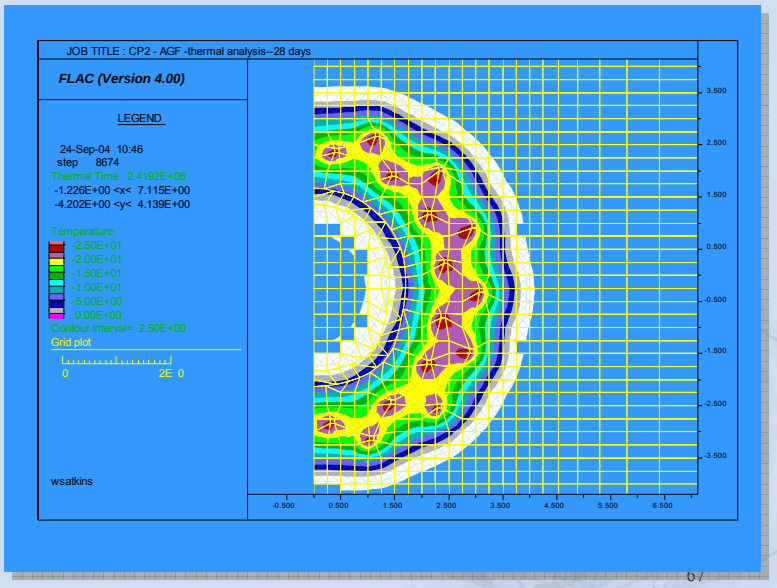
Ground Freezing - Temp. Contours at 2 Weeks



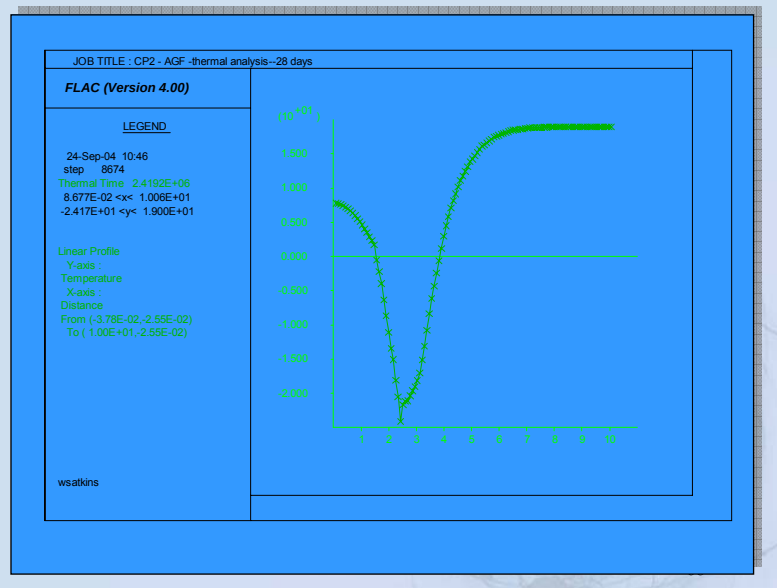
Ground Freezing - Temp. Contours at 3 Weeks



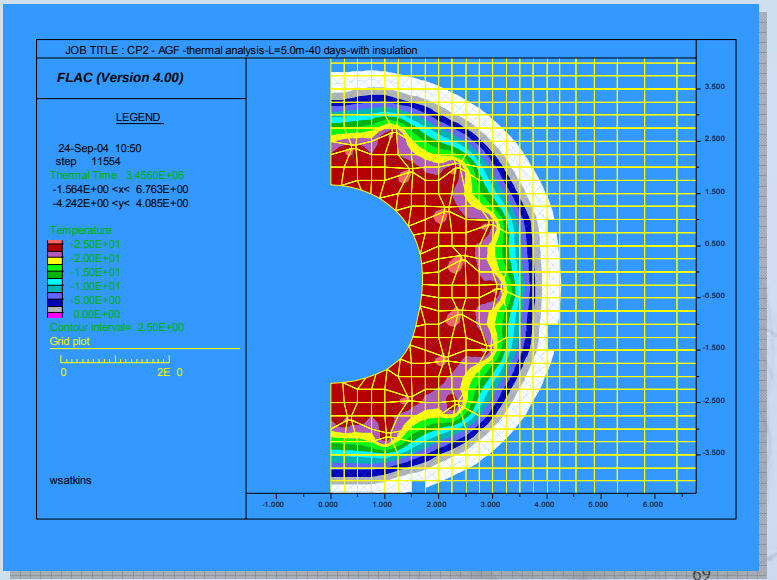
Ground Freezing - Temp. Contours at 4 Weeks



Ground Freezing - Temp. Profile at 4 Weeks



Ground Freezing - Temp. Contours End of Exc



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Notes

- Choose a sympathetic treatment to solve problems of soil-structure interaction.
- Instead of performing a 3D numerical analysis, a 2D numerical analysis (plane strain and “axisymmetric” models) could still achieve fair accurate results by using the deconfinement rate method.

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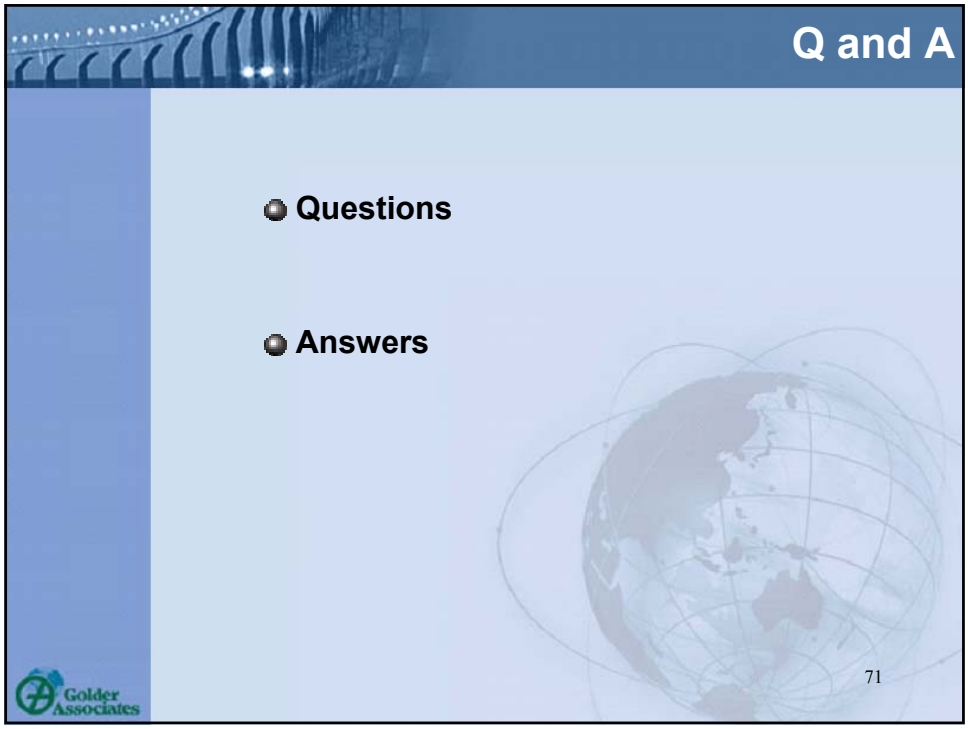
Q and A
Questions
Answers
Golder Associates
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