Lecture 3: Tunnelling under Squeezing Conditions
The term “squeezing rock” originates from the pioneering days of tunnelling through the Alps. It was associated with deformations, damage or destruction of the timber supports used.
**SQUEEZING**

SQUEEZING stands for large time-dependent convergence during tunnel excavation. It takes place when a particular combination of induced stresses and material properties pushes some zones around the tunnel beyond the limiting shear stress at which creep starts. Deformation may terminate during construction or continue over a long period of time.

**SQUEEZING**

SQUEEZING is closely related to the excavation and support techniques which are adopted. If the support installation is delayed, the rock mass moves into the tunnel and a stress redistribution takes place around it. On the contrary, if deformation is restrained, squeezing will lead to long-term load build-up of rock support.
The tunnel convergence, the face extrusion, the rate of deformation and the extent of the yielding zone around the tunnel depend on the geological and geotechnical conditions, the in situ state of stress relative to the rock mass strength, the ground water flow and pore pressure, and the rock mass properties.

The large deformations associated with squeezing may also occur in rocks susceptible to swelling. Although the causes resulting in either a behaviour or the other one are different, it is often difficult to distinguish between squeezing and swelling, as the two phenomena may occur at the same time and induce similar effects.
Exemplifications of the difficulties that can be experienced when tunnelling under squeezing/swelling rock conditions

Gottardo Road Tunnel

San Donato Railway Tunnel
EXAMPLIFICATIONS OF THE DIFFICULTIES THAT CAN BE EXPERIENCED WHEN TUNNELLING UNDER SQUEEZING/SWELLING ROCK CONDITIONS

SAN DONATO RAILWAY TUNNEL

SPARTIACQUE TUNNEL
EXAMPLIFICATIONS OF THE DIFFICULTIES THAT CAN BE EXPERIENCED WHEN TUNNELLING UNDER SQUEEZING/SWELLING ROCK CONDITIONS

DHIARIZOS TUNNEL
EXAMPLIFICATIONS OF THE DIFFICULTIES THAT CAN BE EXPERIENCED WHEN TUNNELLING UNDER SQUEEZING/SWELLING ROCK CONDITIONS

BORGAILO TUNNEL

EXAMPLIFICATIONS OF THE DIFFICULTIES THAT CAN BE EXPERIENCED WHEN TUNNELLING UNDER SQUEEZING/SWELLING ROCK CONDITIONS

ORTE TUNNEL
Different Methods...

1. Jethwa et al. 1984
2. Singh et al. 1992
3. Aydan et al. 1993
4. Goel et al. 1995
5. Hoek and Marinos 2000

Methods...based on different parameters such as:

- Rock Mass Quality Q
- Rock Mass Number N (Q for SRF=1)
- Tunnel Depth H
- Rock Mass Strength/In situ stress ($\sigma_{cm}/p_o$)
- Intact Rock Strength/In situ stress ($\sigma_{ci}/p_o$)

To be discussed: Hoek and Marinos
Tunnel Response during face advances

Rock Mass Strength/In situ Stress (σ\text{cm}/p_0)

Tunnel Wall Displacement/Radius (u_t/a)

ε_t(\%) = 0.15(1 - p_i/p_o)\sigma_{cm}^{-(3p_i/p_o+1)/(3.8p_i/p_o+0.54)}

0.00
0.05
0.10
0.15
0.20
0.25

(p_i/p_o)

Radial displacement of tunnel

Longitudinal displacement of tunnel face ("extrusion")

Heading

Core ahead of tunnel

σ_1

σ_2

σ_3
\[ \varepsilon_f(\%) = 0.1 \left(1 - \frac{p_i}{p_o}\right)^{\frac{\sigma_{cm}}{p_o}} \left(3.8 \frac{p_i}{p_o} + 0.54\right) \]
The question in tunnelling

How to avoid the tunnel wooden support failure, if not the tunnel collapse?

1850

1985

“Capolavori di Minuseria” (Politecnico di Torino)

Italian Method

Excavation and support methods: the “past”
Excavation and support methods: the “present”

One of the above methods generally applied for construction of tunnels with span greater than 10 m (typically 100 m² cross section or greater, up to 160 m²)

Even for shallow transportation tunnels, the full face method tends to be favored with respect to the other two methods. This is certainly the case in Italy

The tunnel is driven ahead by relying on reinforcement of the face and of the ground surrounding the heading. Frequent use is made of fiberglass elements
Top heading and benching down method

Full face excavation method
MARINASCO TUNNEL

USE OF: Yielding Steel Ribs
USE OF:
• YIELDING STEEL RIBS
• YIELDING BOLTS
• LINING STRESS CONTROLLERS

Before convergence

Following convergence

Yielding Bolts
USE OF:
- YIELDING ELEMENTS

METHODS FOR DESIGN ANALYSIS OF TUNNELS IN SQUEEZING CONDITIONS

SHOULD CONSIDER

THE THREE-DIMENSIONAL STATE OF STRESS NEAR THE TUNNEL FACE

THE ONSET OF YIELDING WITHIN THE ROCK MASS, AS DETERMINED BY THE SHEAR STRENGTH PARAMETERS RELATIVE TO THE INDUCED STRESS

THE TIME DEPENDENT BEHAVIOUR
The use of numerical analyses is advisable when the rock mass strength/in situ stress ratio is below 0.3 and it is highly recommended if this ratio falls below about 0.15, when the stability of the tunnel face may become a critical issue.

### Graph: Rock Mass Strength/In situ stress vs. Tunnel Wall Displacement/Radius

- **Strain greater than 10%**: Extreme Squeezing
- **Strain between 5 and 10%**: Very severe Squeezing
- **Strain between 2.5 and 5%**: Severe Squeezing
- **Strain between 1 and 2.5%**: Minor Squeezing
- **Strain less than 1%**: No Squeezing

### Diagram: 3D Analyses Advisable

3D Analyses advisable

Longitudinal Section

Transversal Section A-A

Methods for Design Analysis
3D Analyses advisable

Influence of 3D Conditions

Stress path at point C (crown), I (invert), S (sidewall)

Methods for Design Analysis

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3D Analyses advisable

Influence of 3D Conditions

Stress path at point F (face of the excavation)

Methods for Design Analysis
Methods for Design Analysis

3D Analyses advisable

Maximum displacement = 44 mm

Onset of yielding around the tunnel

Methods for Design Analysis
SIMPLIFIED METHODS OF ANALYSIS AND DESIGN OF TUNNELS IN SQUEEZING CONDITIONS

CONSIDER

THE ONSET OF YIELDING WITHIN THE ROCK MASS, AS DETERMINED BY THE SHEAR STRENGTH PARAMETERS RELATIVE TO THE INDUCED STRESS

Elasto-plastic closed form solutions for rock mass response to excavation of a circular tunnel can be used.

If the rock mass is assumed to behave as an elasto-plastic isotropic medium, the following models can be adopted:

- Elastic perfectly plastic (a)
- Elasto-plastic with strain softening behaviour (b)
- Elasto-plastic, with brittle behaviour (c)

(e.g. Brown et al., 1983; Carranza-Torres and Fairhurst, 1999)
Based upon the above solutions, dimensionless plots can be derived from the results of parametric studies where the influence of the variation in the input parameters are studied by the Monte Carlo analysis, under the assumption of elastic perfectly plastic behaviour of the rock mass, with zero volumetric change (Hoek, 1998, 1999).

**Time-dependent behaviour**

**Rock Mass Behaviour**

- Time Independent
  - Elastic
  - Plastic
- Time Dependent
  - Delayed Elastic
  - Time Dependent peak and ultimate strength

Methods for Design Analysis:

1. Strain - hardening
2. Perfectly plastic
3. Strain softening

\[
\mu_c = 0.002 \left( \frac{\sigma_{cm}}{P_0} \right)^{-2}
\]

\[
R_{pl} = 1.25 \left( \frac{\sigma_{cm}}{P_0} \right)^{-0.57}
\]
Introduzione

EXCAVATION OF LARGE SPAN TUNNELS BY THE FULL FACE METHOD WITH GROUTED FIBERGLASS DOWELS IN FACE

RATICOSA TUNNEL - Clay-Shales (BOLOGNA - FIRENZE HIGH SPEED RAILWAY LINE) COURTESY OF ROCKSOIL - CAVET - ITALFERR
Full Face Excavation/Support/Reinforcement Sequence Through Weak Rock (Monghidoro Flysch)

Monte Bibele Tunnel High Speed Railway Line Bologna - Firenze

Fiberglass Dowels

Current Stage

Invert Lining

Shotcrete and Steel Stets

Forepole Umbrella (whenever required)

Fiberglass Dowels Previous Stage (overlap)

Drainage Holes

Fiberglass Dowels Current Stage

Full Face Excavation/Support/Reinforcement Sequence Through Weak Rock Schematic Illustration - not to scale
Mucking-Out with face stabilisation completed and prior to new face advance stage (typically 1 m).

Drilling Unit for Installation of Fiberglass Face Reinforcement

Steel Sets installed as close to the face as possible

Optical Target for Convergence Measurements

Hole in the face to be drilled

Fiberglass Dowell being grouted
3

Installation of Heavy Steel Sets as close to the face as possible followed by Application of Shotcrete

4

Installation of Invert Struts close to the face to control floor heave and to “close the ring”
5

Invert Reinforced Concrete Lining installed as close to the face as possible

6

Installation of Final Concrete Lining backed by a PVC Membrane and a Geotextile Drainage Layer
Lesson Learnt: Extrusion measurements more relevant than convergence measurements for understanding rock mass response
(Case Study: Raticosa Tunnel)

Creep Tests in undrained conditions on clay-shales for the study of time dependent response of tunnel face

(q/qf = mobilised strength)
The viscoplastic strains depend on the deviatoric stress state only and do not induce volumetric strains.
- axis-symmetric conditions
- circular cross section
- initial state of stress constant and isotropic
- coupled analysis in undrained conditions
- two cases considered:
  - Osteria Access Adit (depth = 148 m)
    Mohr-Coulomb elasto-plastic perfectly plastic model
  - Raticosa Tunnel (depth = 50 m)
    Elasto visco-plastic model
Raticosa Tunnel

Tunnels Underground Excavations

Design Analyses Case Studies and Observed Performance

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