WORKSHOP ON OBSERVATIONAL APPROACH IN TUNNELLING: EVOLVEMENT, ISSUES AND CHALLENGES

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Overview of Topics

- Tunnel Design - Approaches
- Specificities and Stages of (NATM) Tunnel Design
- Support Measures - Choices, Constraints and Implementation

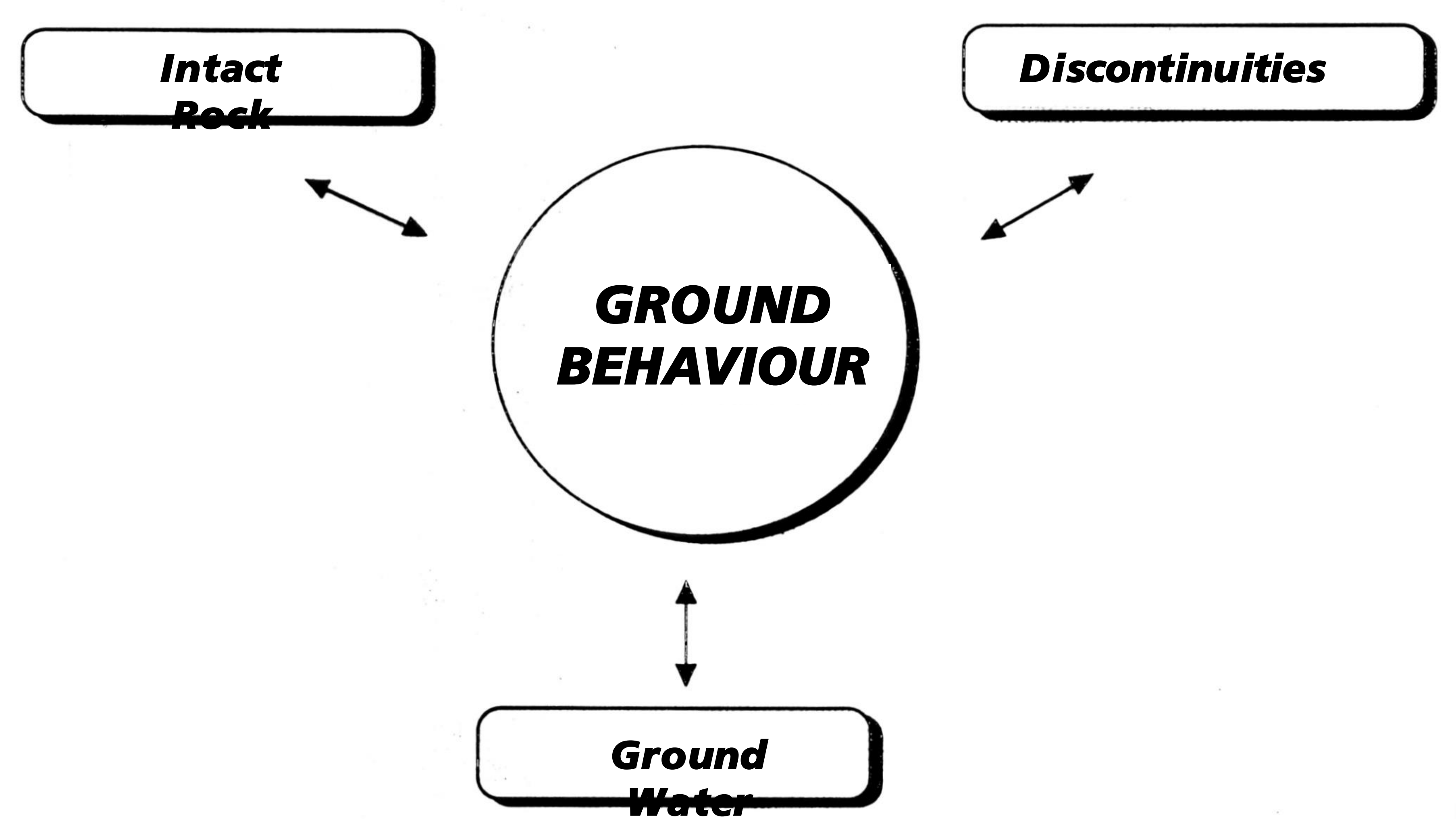
Approaches to Tunnel Design

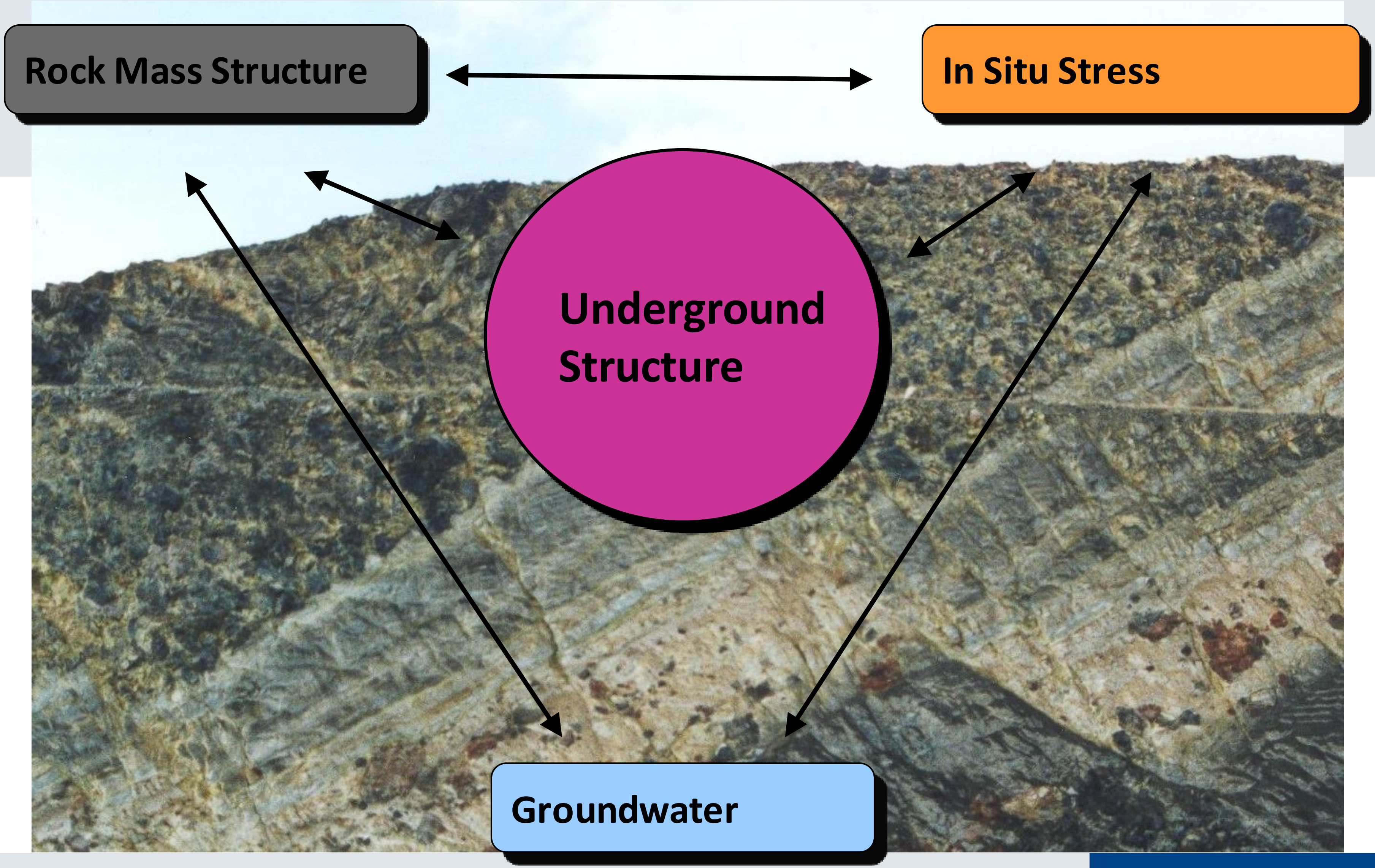
- Overview, Starting Point – describing the ground
- Terzaghi's rock classification, Q -System
- Parameters and Analytical Checks

Approaches to Tunnel (Support) Design

- Empirical Design, from experience in comparable circumstances
  - Terzaghi – ASSM approach, “load”
- Empirical Support “Design” based on Index Values
  - Q-System (diagram)
  - RMR (description of support for index ranges)
- Analytical Calculations
  - Calculations for stress and stability checks - predimensioning
  - Duddeck / Erdmann
  - Muir / Wood
  - Ground Reaction Curve
- Numerical Simulations (FE, FD, BE; 2D and 3D)

Interactions




Rock Mass Structure
In Situ Stress
Underground Structure
Groundwater

Terzaghi

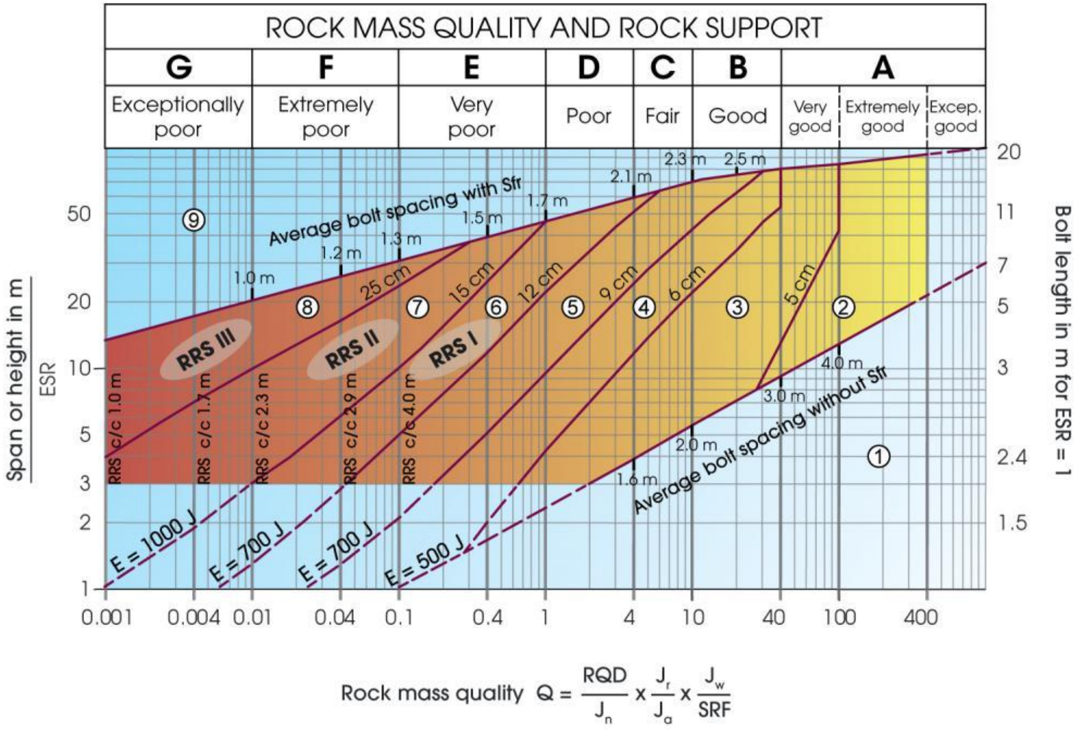
- Description of the rock mass
- It describes the rock load – means the support must be dimensioned analytically
- It describes some phenomena
- It recommends certain support types

Rock Class	Definition	Rock Load Factor Hp (in feet, B and Ht in feet)	Remark
I. Hard and intact	Hard and intact rock contains no joints and fractures. After excavation, the rock may have popping and spalling at excavated face.	0	Light lining required only if spalling or popping occurs.
II. Hard stratified and schistose	Hard rock consists of thick strata and layers. The interface between strata is cemented. Popping and spalling at the excavated face is common.	0 to 0.5 B	Light support for protection against spalling. Load may change between layers.
III. Massive, moderately jointed	Massive rock contains widely spaced joints and fractures. Block size is large. Joints are interlocked. Vertical walls do not require support. Spalling may occur.	0 to 0.25 B	Light support for protection against spalling.
IV. Moderately blocky and seamy	Rock contains moderately spaced joints. Rock is not chemically weathered and altered. Joints are not well interlocked and have small apertures. Vertical walls do not require support. Spalling may occur.	0.25 B to 0.35 ($B + H_t$)	No side pressure.
V. Very blocky and seamy	Rock is not chemically weathered and contains closely spaced joints. Joints have large apertures and appear separated. Vertical walls need support.	(0.35 to 1.1) ($B + H_t$)	Little or no side pressure.
VI. Completely crushed but chemically intact	Rock is not chemically weathered and highly fractured with small fragments. The fragments are loose and not interlocked. Excavation face in this material needs considerable support.	1.1 ($B + H_t$)	Considerable side pressure. Softening effects by water at tunnel base. Use circular ribs or support rib lower end.
VII. Squeezing rock at moderate depth	Rock slowly advances into the tunnel without a perceptible increase in volume. Moderate depth is considered as 150 ~ 1000 m.	(1.1 to 2.1) ($B + H_t$)	Heavy side pressure. Invert struts required. Circular ribs recommended.
VIII. Squeezing rock at great depth	Rock slowly advances into the tunnel without a perceptible increase in volume. Great depth is considered as more than 1000 m.	(2.1 to 4.5) ($B + H_t$)	
IX. Swelling rock	Rock volume expands (and advances into the tunnel) due to swelling of clay minerals in the rock at the presence of moisture.	up to 250 feet, irrespective of B and H_t	Circular ribs required. In extreme cases use yielding support.

Notes: The tunnel is assumed to be below the ground water table. For tunnel above water tunnel, Hp for Classes IV to VI reduces 50 %.
The tunnel is assumed excavated by blasting. For tunnel boring machine and road header excavated tunnel, Hp for Classes II to VI reduces 20 - 25 %.

Q - System

- Required input:
  - Span
  - ESR (excavation support ratio) – depending on the importance of the structure
  - Q – value derived from
    - RQD
    - Joint set number, Joint roughness, Joint alteration, Joint water
    - Stress Reduction Factor (SRF)
- Limitations outlined in the Handbook (NGI, 2022)

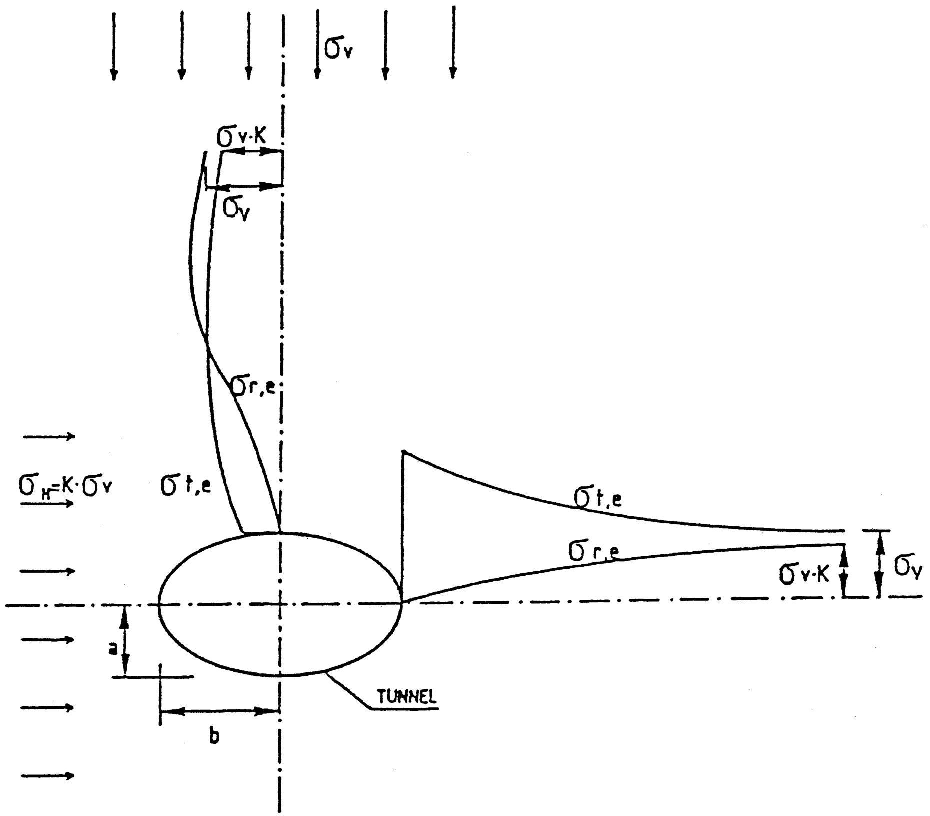


Basis for Analytical and Numerical Calculations - Parameters

- Stress Field, K_0 value, inclination of principal stress tensors
- Strength parameters (e.g. ϕ , c)
- Deformability / Stiffness
- Spatial parameters like joint set orientations, spacing and joint properties
- Permeability / conductivity
- unit weight, water content

They come from geotechnical investigations, desk studies, adjacent projects

Stress Distribution around an elliptical Underground Excavation



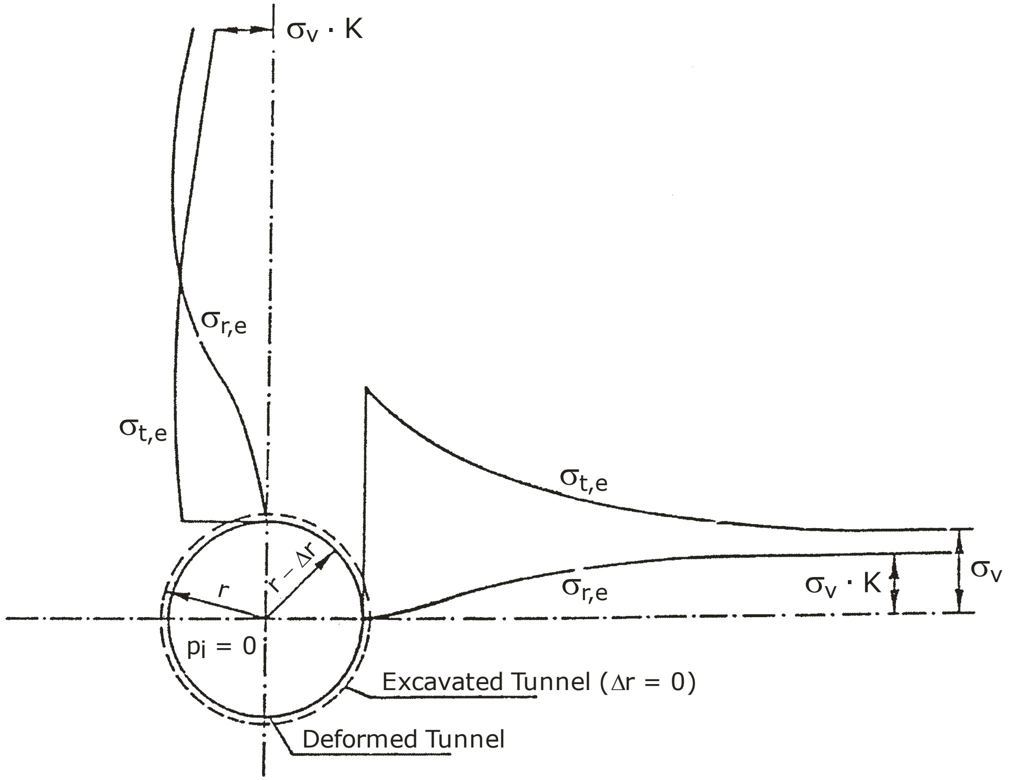
Crown and Invert:

$$\sigma_{t,e} = \sigma_v \cdot \left[\left(2 \cdot \frac{a}{b} + 1 \right) \cdot K - 1 \right]$$

Sidewalls:

$$\sigma_{t,e} = \sigma_v \cdot \left[2 \cdot \frac{b}{a} + 1 - K \right]$$

Stress Distribution around a circular Underground Excavation



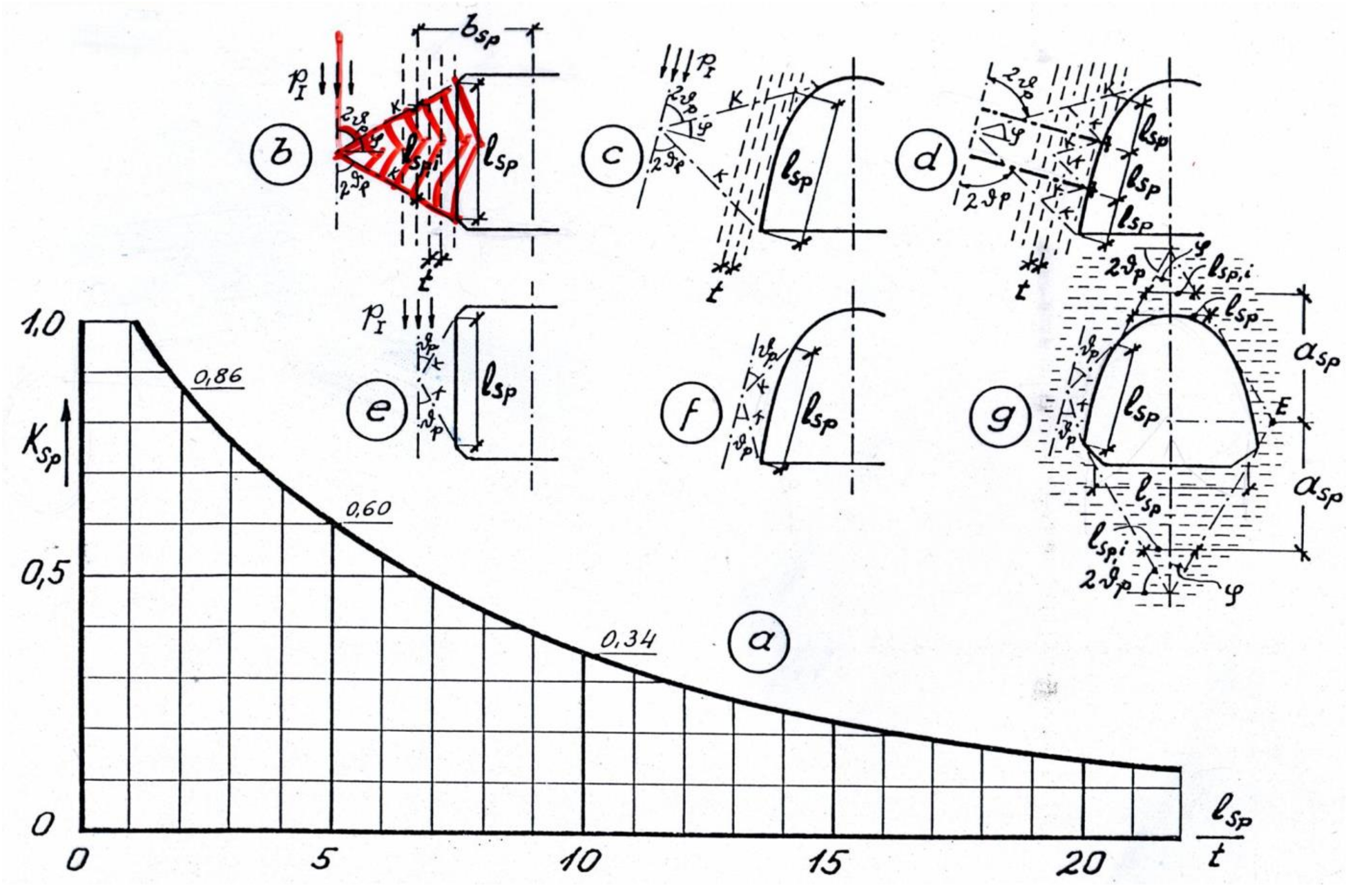
Crown and Invert:

$$\sigma_t = \sigma_v \cdot [3 \cdot K - 1]$$

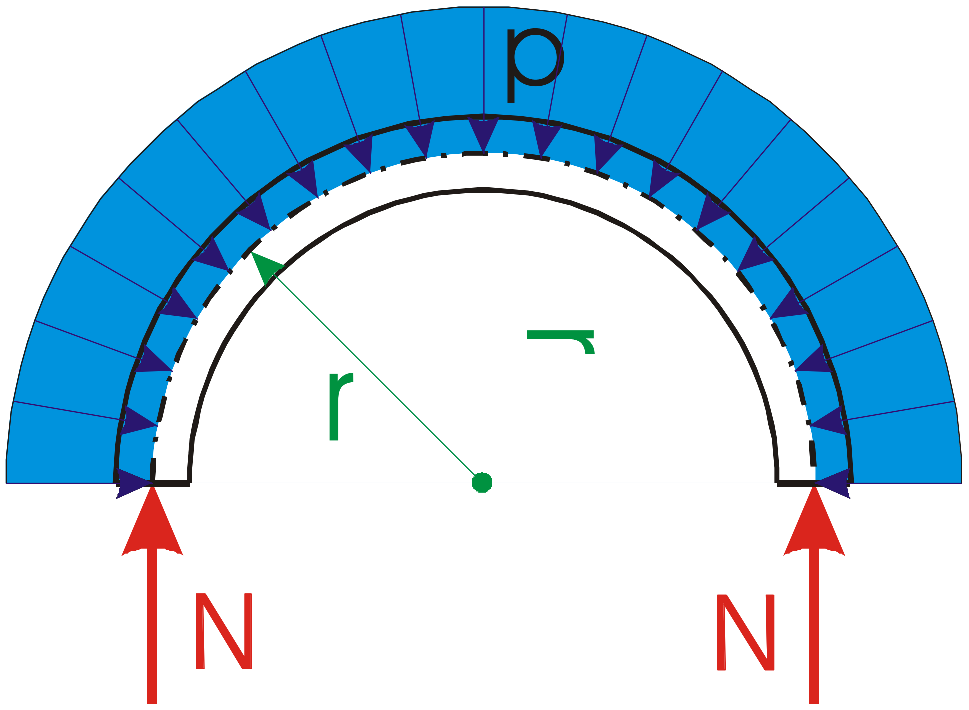
Sidewalls:

$$\sigma_t = \sigma_v \cdot [3 - K]$$

Strength reduction of bedded rock mass



Ring Formula – first estimate of support stress



Normal force per m of lining

$$N = p \cdot r \quad [N/m]$$

Stress in Lining

$$\sigma = \frac{N}{A} = \frac{N}{d_s \cdot 1} \quad [Pa]$$

Caveat for numerical modelling: CHILE vs DIANA

- C – Continuous
- H – Homogeneous
- I – Isotropic
- L – Linear
- E – Elastic

This is how we model in many cases…

- D – Discontinuous
- I – Inhomogeneous
- A – Anisotropic
- N – Not
- E – Elastic

… and this is the reality, especially for rock mass.

Specificities and Stages of (NATM) Tunnel Design

- "Austrian Guideline" (2010) – overview and specific explanations
- Design and Construction Phase

The Austrian Guideline (OeGG, 2010)

- Formalizes the "Austrian Way" for Cyclic Excavation (Conventional Tunnelling) according to NATM
- Outlines the steps to be taken, reflecting the conditions required by EC 7 for Observational Approach
- Prescribes
  - the steps to be taken during Design Phase
  - the procedures during Construction Phase

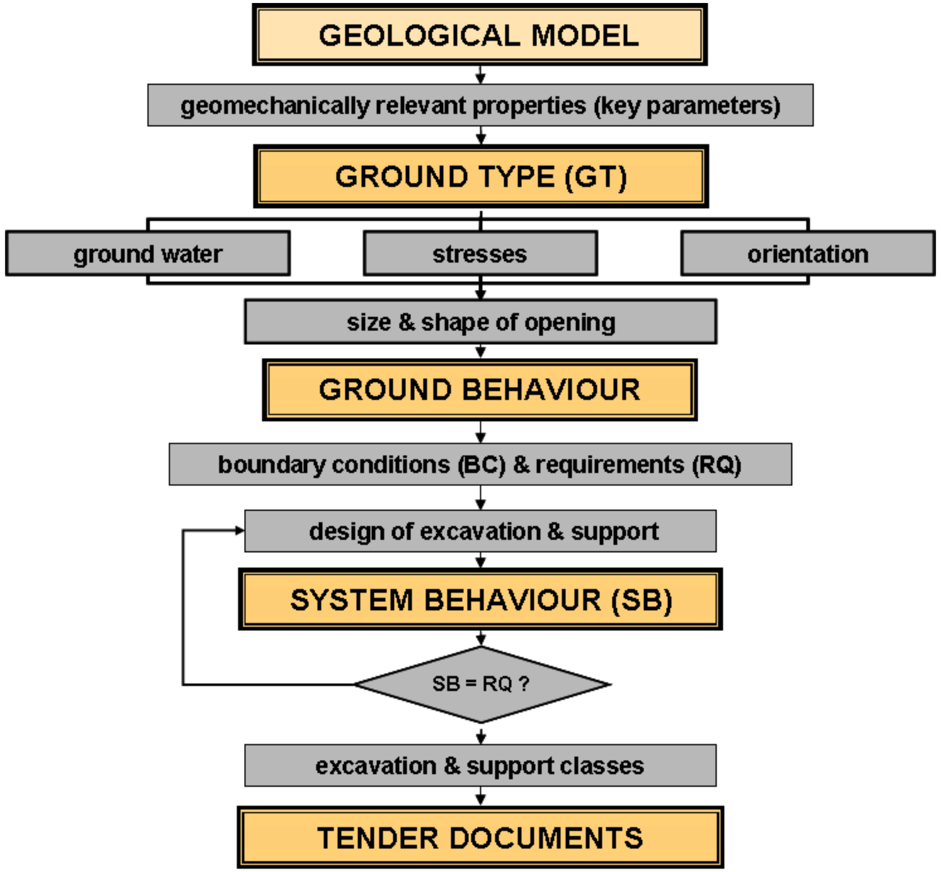
Austrian Guideline – Classification

- **Ground Type** — Ground with similar properties
- **Ground Behaviour Type** — Ground with similar behavior with respect to excavation, spatial and time dependent behavior and failure mode.
- **System Behaviour** — Behaviour resulting from the interaction between ground and support for the applied excavation sequence

Design Phases

1. Design Stages
    - Preliminary design
    - Tender Design
    - Detailed Design
2. Construction
    - Choice of support according to design (framework plan)
    - Validation of the design
    - Design modifications if and as required

Design Phase - Rock Mass Classification and Development of Excavation & Support Classes



Geomechanical Design – Procedure 1

1st STEP

2nd STEP

3rd STEP

4th STEP

5th STEP

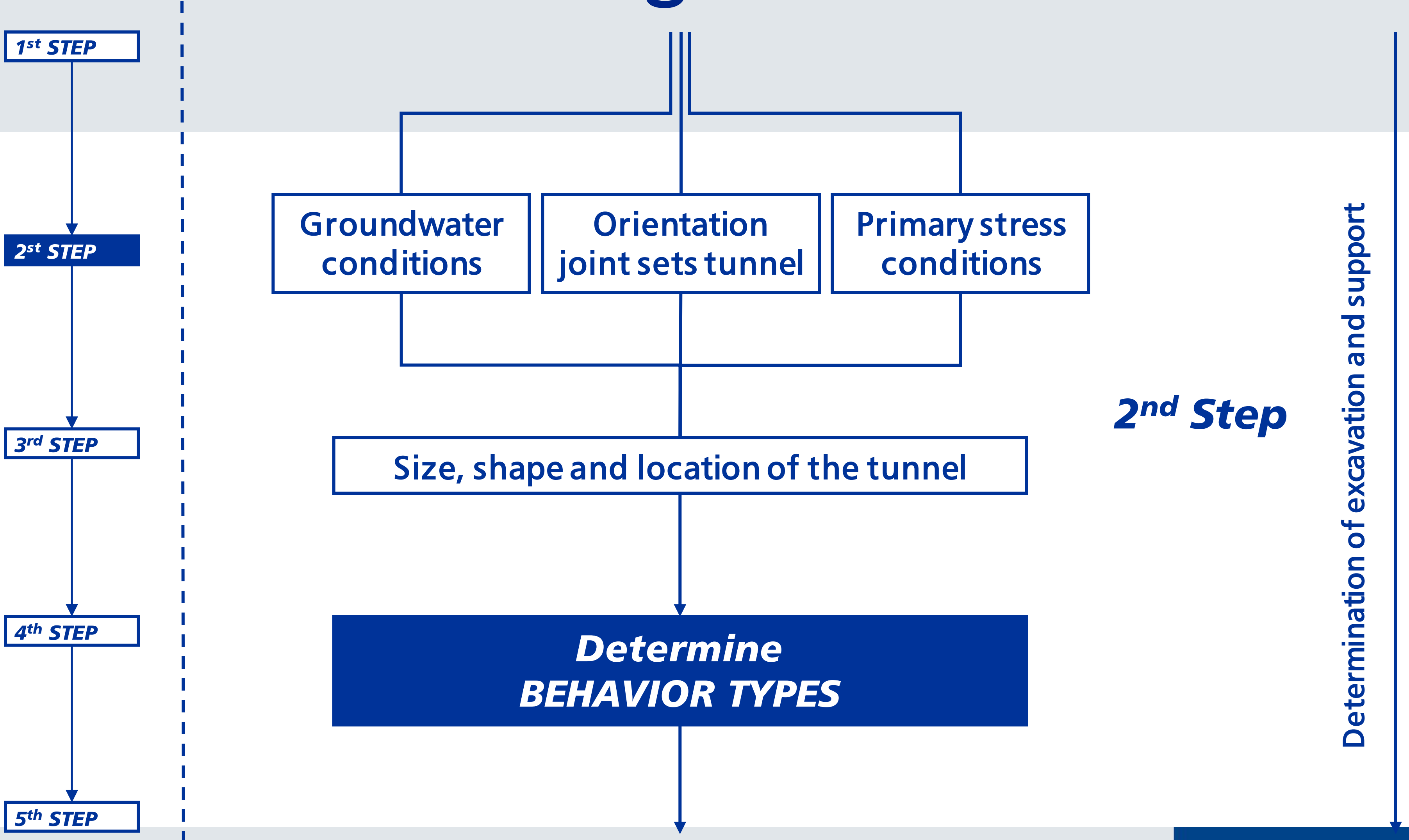
Geomechanically relevant parameters

Determine GROUND TYPES

1st Step

Determination of excavation and support

Geomechanical Design – Procedure 2



Ground Behaviour Types

Basic categories of Behaviour Types (BT)		Description of potential failure modes/mechanisms during excavation of the unsupported ground
1	Stable	Stable ground with the potential of small local gravity induced falling or sliding of blocks
2	Potential of discontinuity controlled block fall	Voluminous discontinuity controlled, gravity induced falling and sliding of blocks, occasional local shear failure on discontinuities
3	Shallow failure	Shallow stress induced failure in combination with discontinuity and gravity controlled failure
4	Voluminous stress induced failure	Stress induced failure involving large ground volumes and large deformation
5	Rock burst	Sudden and violent failure of the rock mass, caused by highly stressed brittle rocks and the rapid release of accumulated strain energy

Basic categories of Behaviour Types (BT)		Description of potential failure modes/mechanisms during excavation of the unsupported ground
6	Buckling	Buckling of rocks with a narrowly spaced discontinuity set, frequently associated with shear failure
7	Crown failure	Voluminous overbreaks in the crown with progressive shear failure
8	Ravelling ground	Ravelling of dry or moist, intensely fractured, poorly interlocked rocks or soil with low cohesion
9	Flowing ground	Flow of intensely fractured, poorly interlocked rocks or soil with high water content
10	Swelling ground	Time dependent volume increase of the ground caused by physical-chemical reaction of ground and water in combination with stress relief
11	Ground with frequently changing deformation characteristics	Combination of several behaviours with strong local variations of stresses and deformations over longer sections due to heterogeneous ground (i.e. in heterogeneous fault zones; block-in-matrix rock, tectonic melanges)

Remark on Ground Behaviour

In case of unwanted / unmanageable ground behaviour, what needs to be done to make it more manageable (apart from "support") ?

- Change of Method (closed TBM instead of NATM)
- Ground improvement through different measures, out of the fields of
  - Drainage
  - Grouting

basically to change (locally) the ground behaviour

Geomechanical Design – Procedure 3

1st STEP

2nd STEP

3rd STEP

4th STEP

5th STEP

Identification of boundary conditions

Definition of requirements (RQ)

Determine EXCAVATION and SUPPORT

3rd Step

Determination of excavation and support

Identification of Boundary Conditions

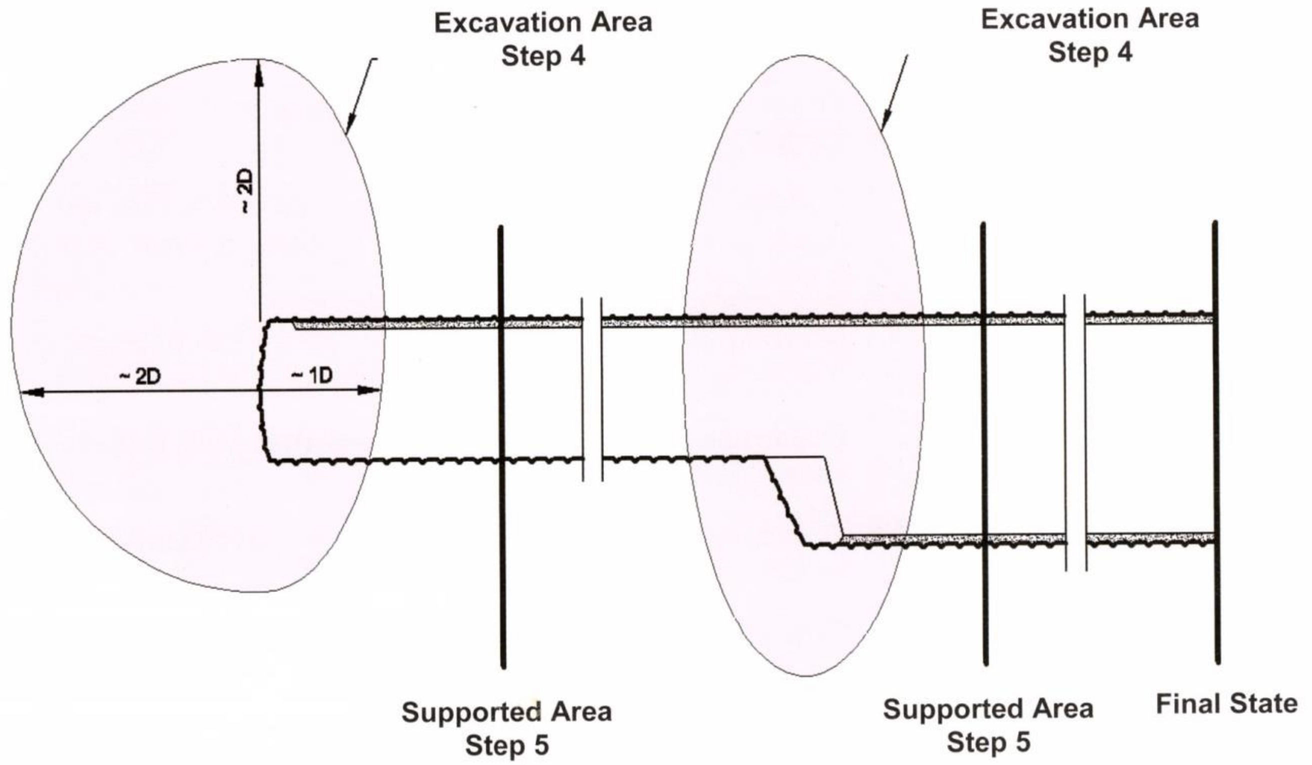
Boundary Conditions = Conditions, which influence construction process and methods due to other than geotechnical reasons

- Working Season
- Altitude
- Availability of specific materials and equipments
- Availability of (qualified) manpower
- Contractual Boundary Conditions

Definition of Requirements

- How much displacement is tolerable ? Stiff or ductile support ?
- Is settlement acceptable ?
- Can the groundwater be lowered ?
- Do I want to apply a factor of safety for my support system?
- What is the anticipated reaction time – shallow tunnelling vs. deep tunnelling?

Sections for System Behavior



Analysis of System Behaviour - I

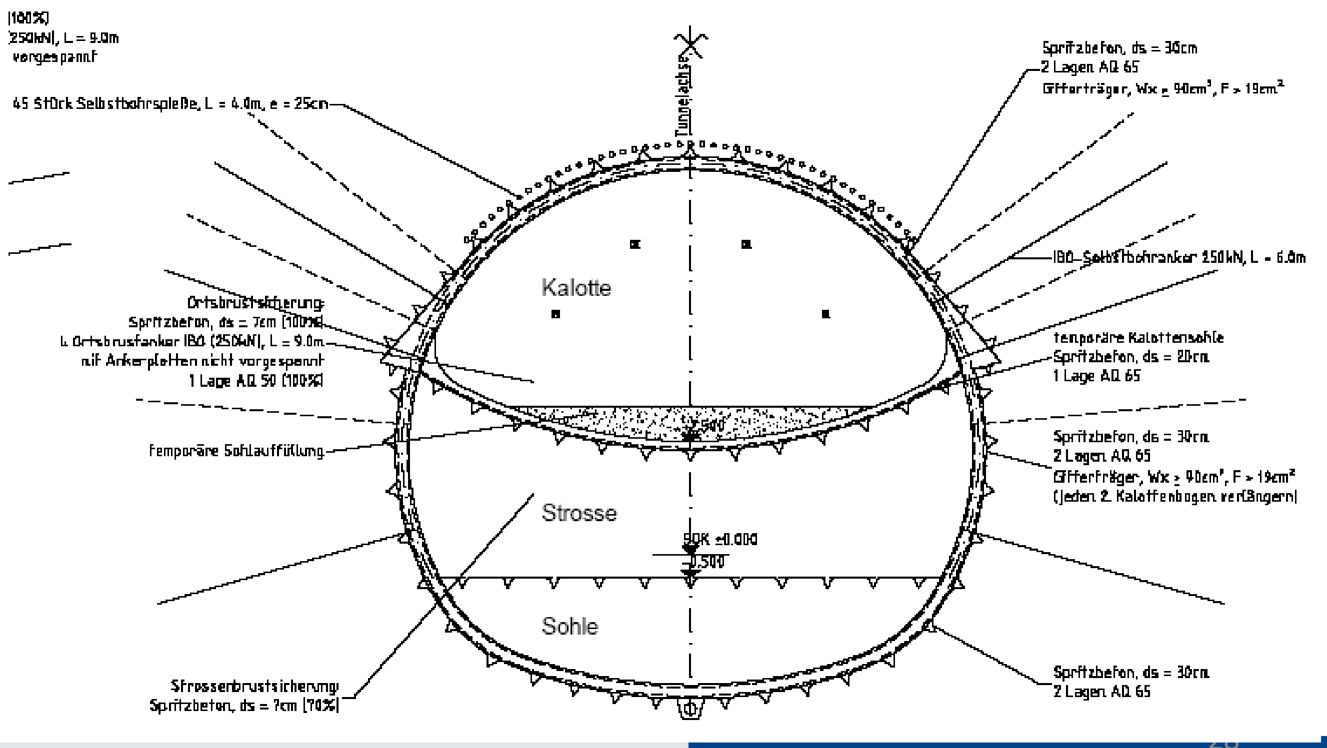
EXAMPLE:
Tunnel Lot H-5
Twin-track railway tunnel
Section km 55+110 to 55+200

Expected ground: Gravel, sand

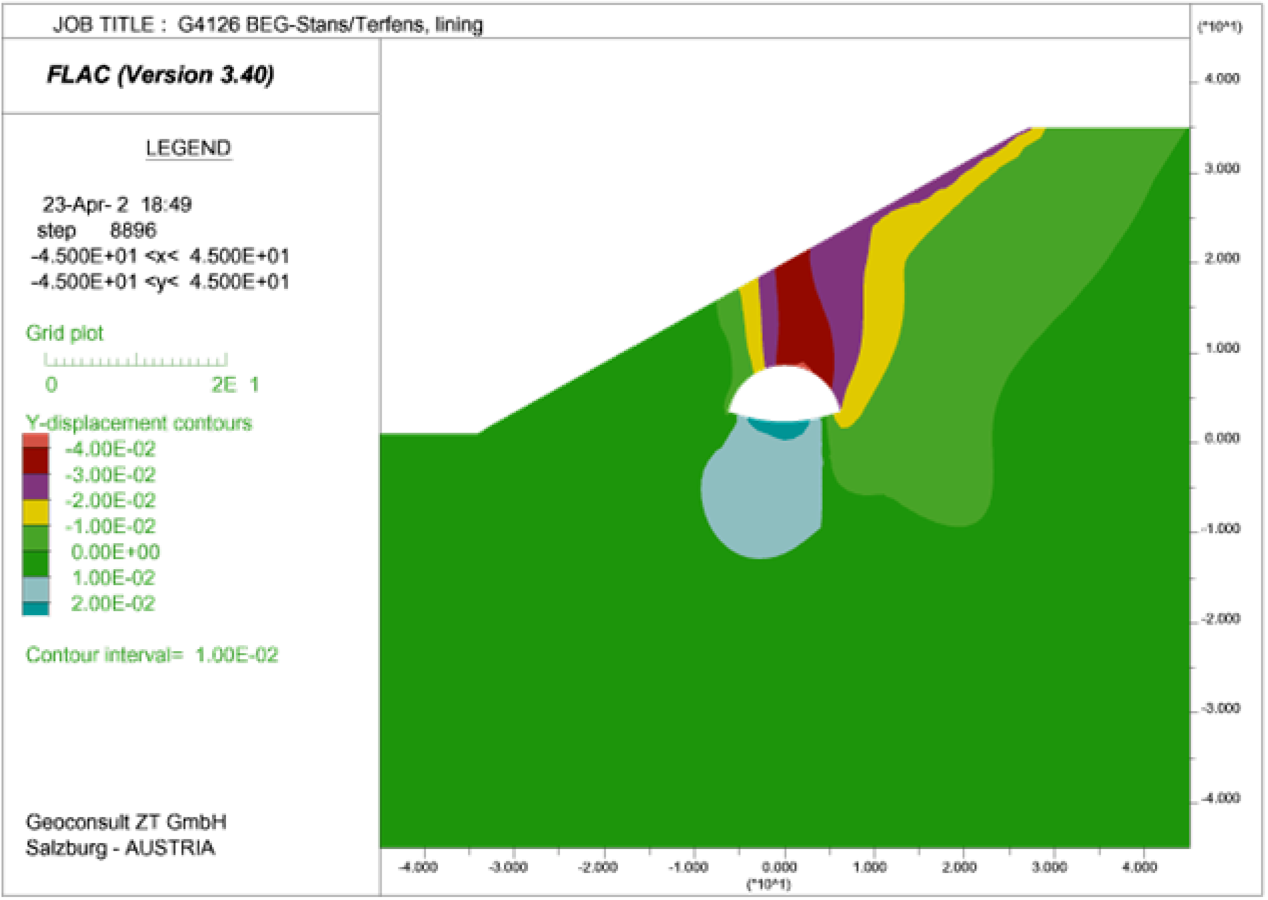
Used ground parameters

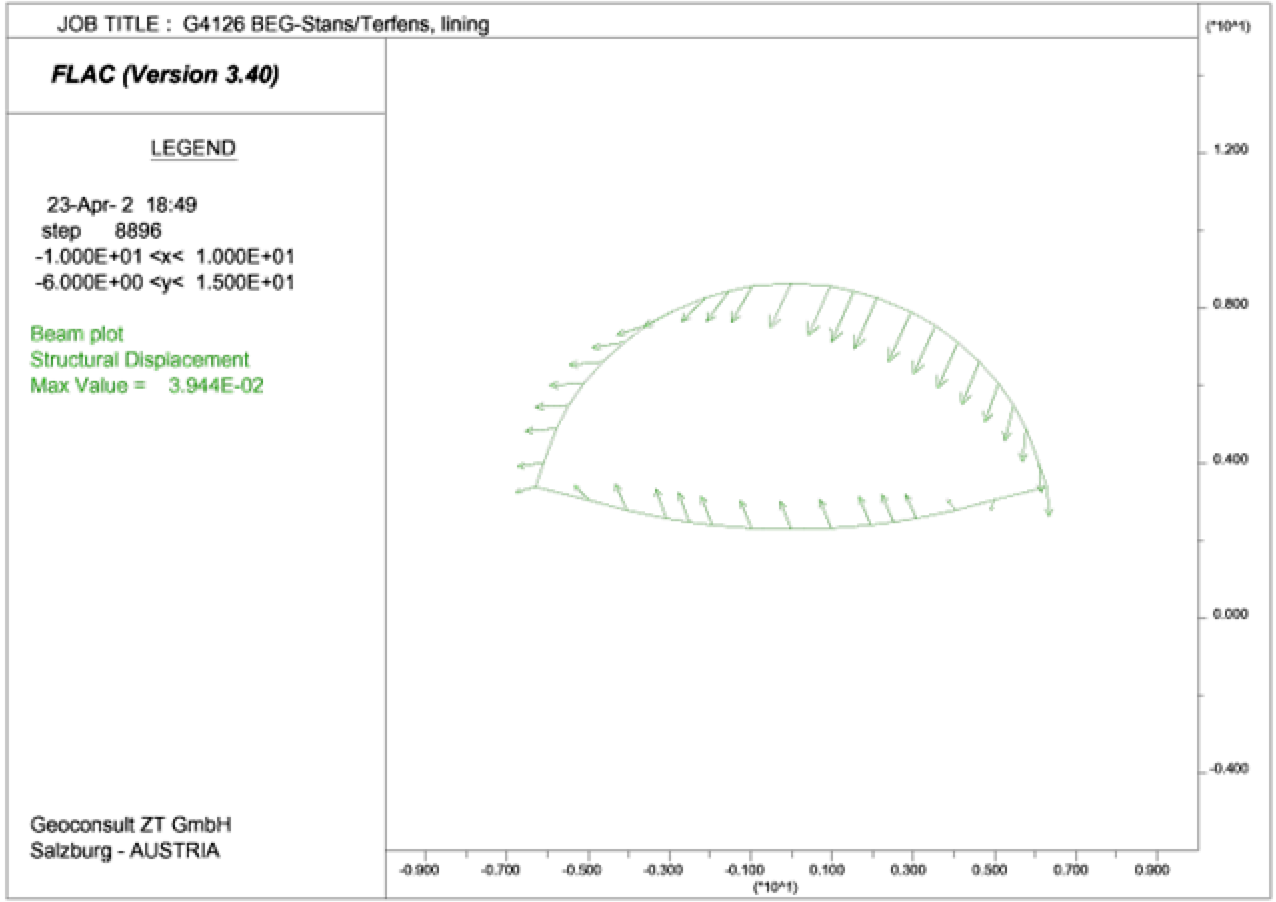
γ´	φ´	c´	E	ν
[KN/m³]	[°]	[MPa]	[MPa]	[-]
22,0	37,0	0,0	60	0,3

Geometry used for calculation

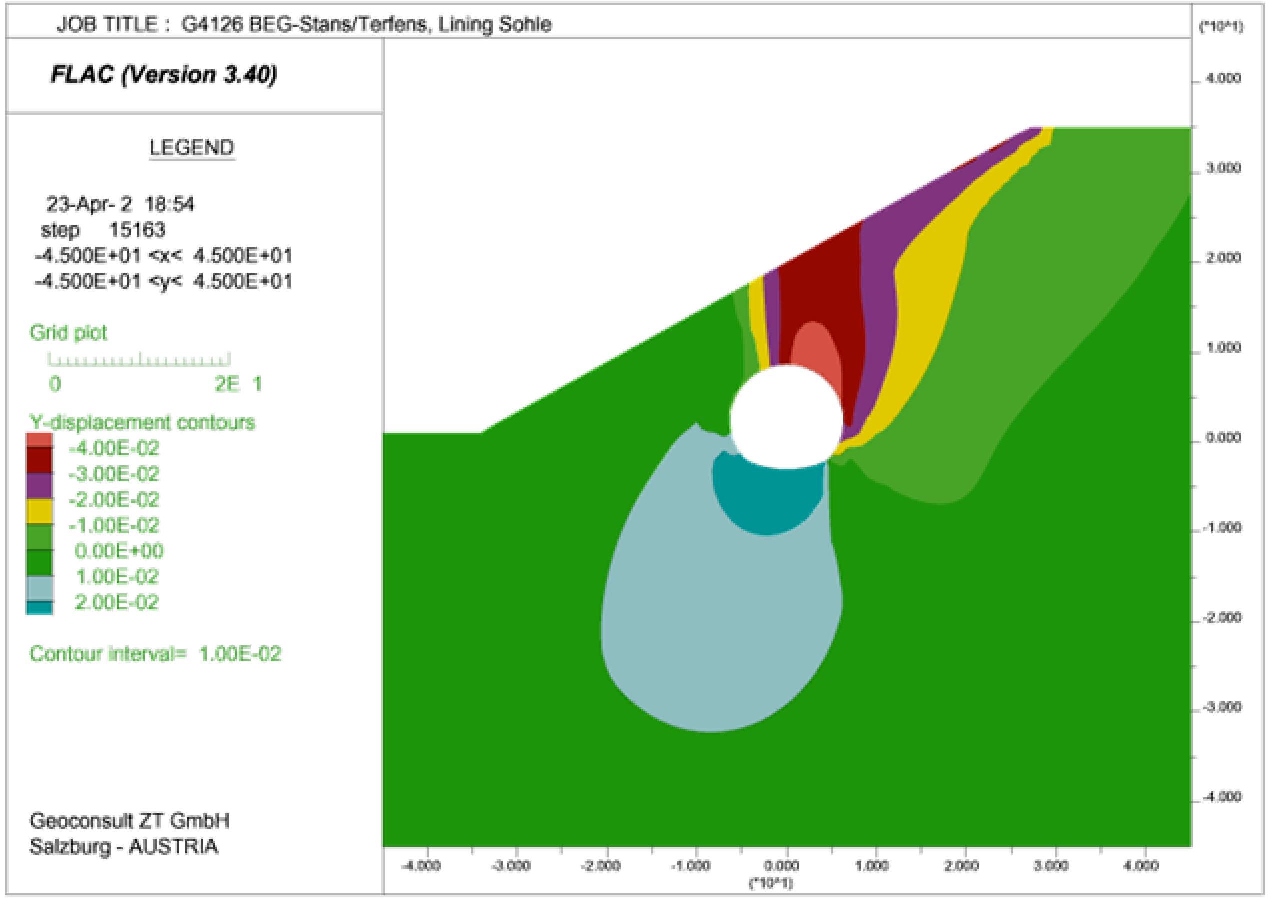


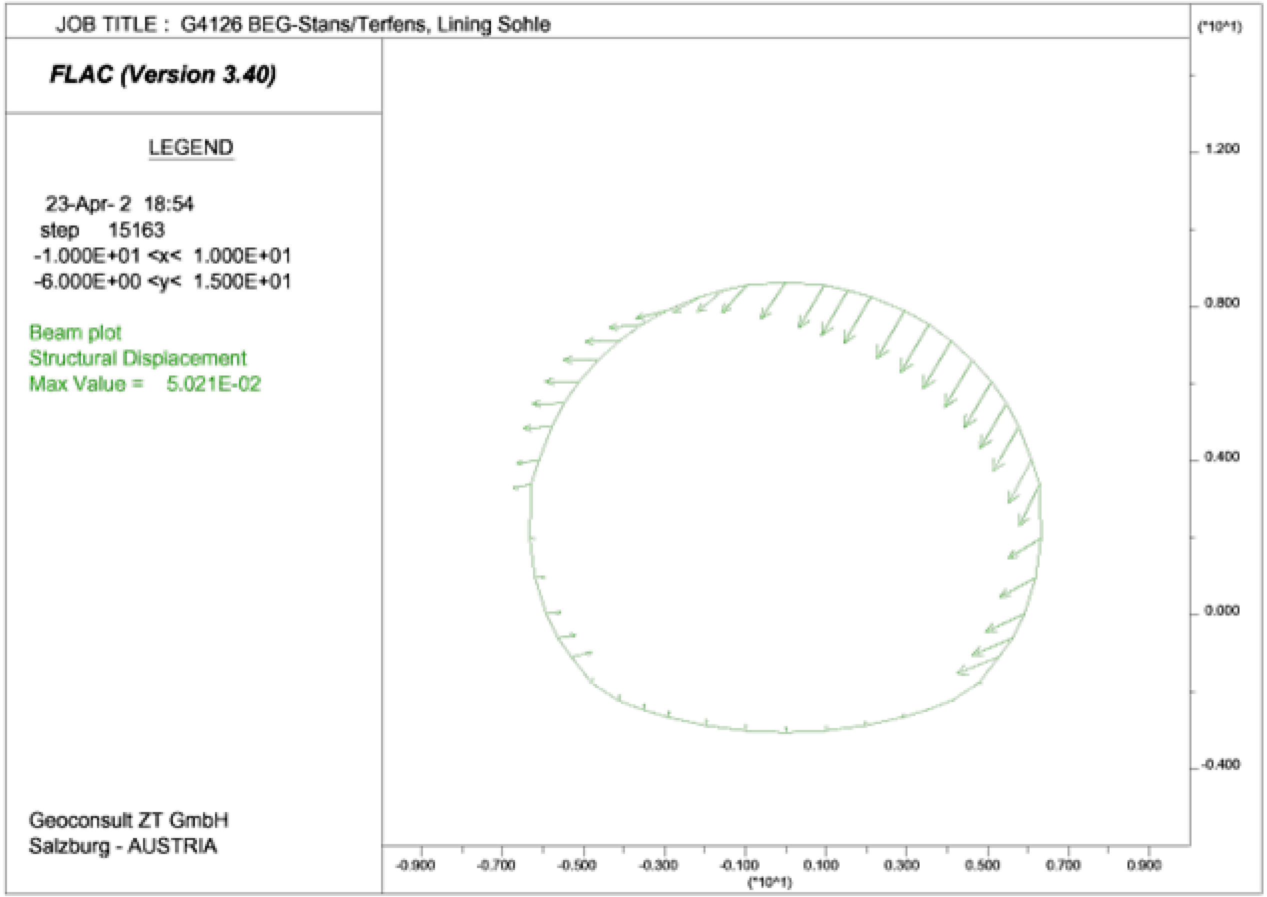
Analysis of System Behaviour - IIa



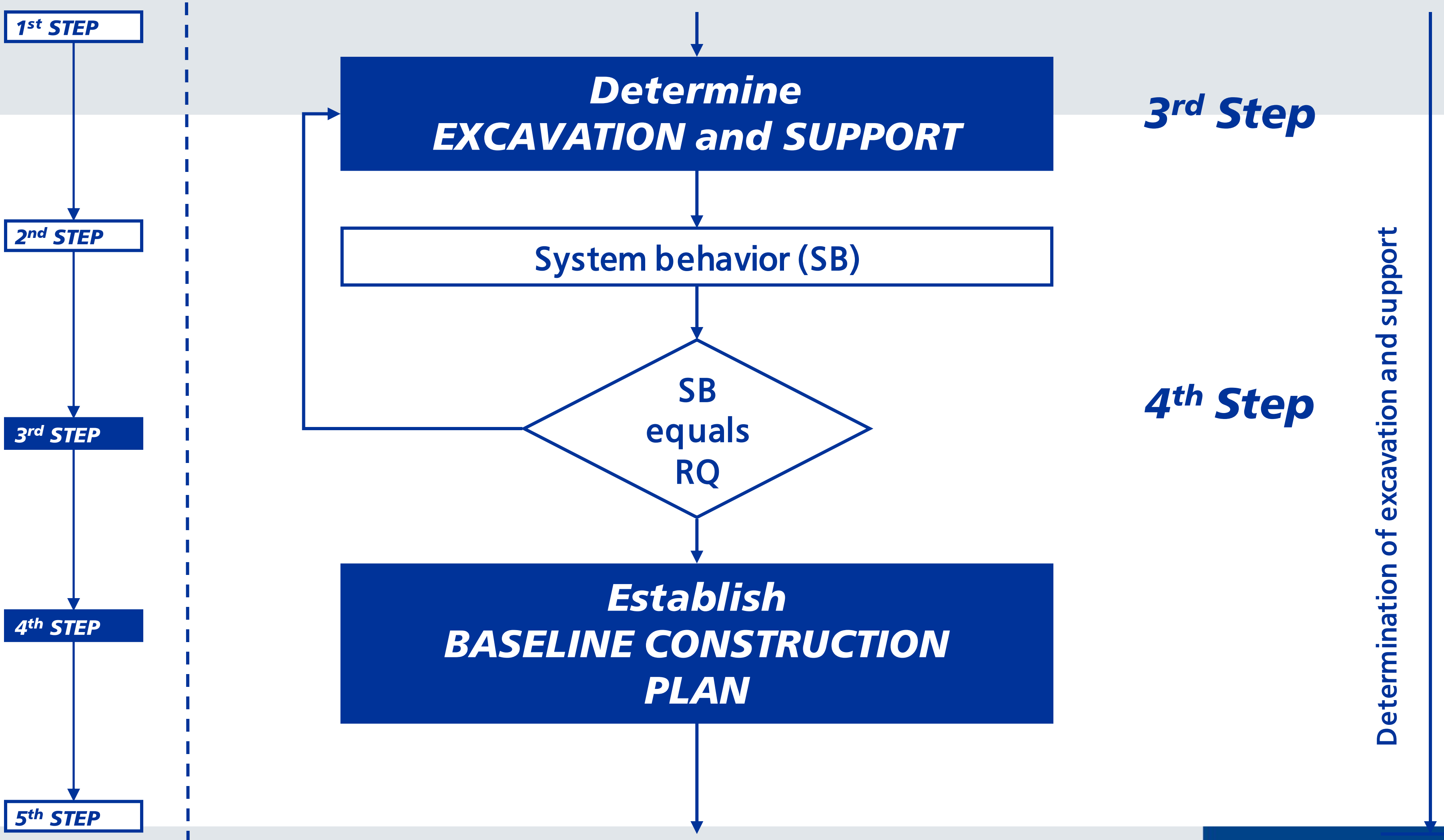


Analysis of System Behaviour - IIb





Geomechanical Design – Procedure 4



Geomechanical Design – Procedure 5

1st STEP
2nd STEP
3rd STEP
4th STEP
5th STEP

Determine EXCAVATION CLASSES

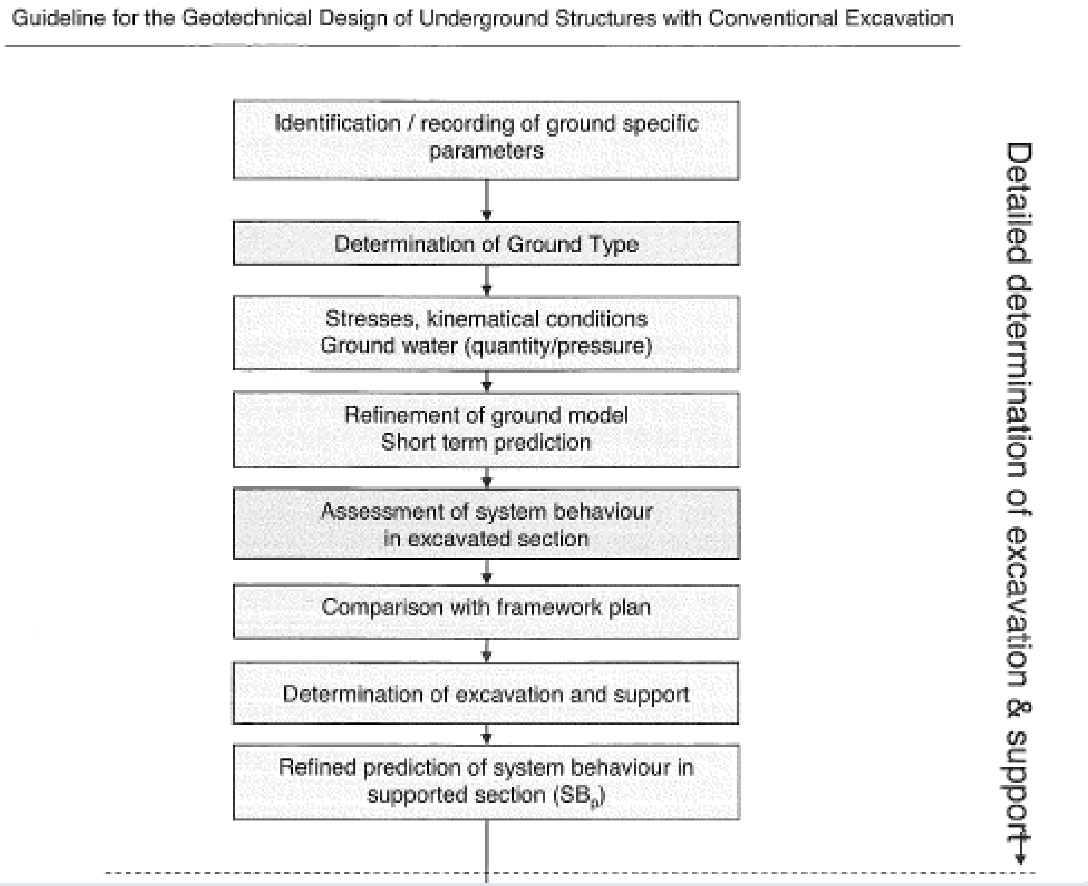
Distribution of Excavation Classes

Documents for the tender

5th Step

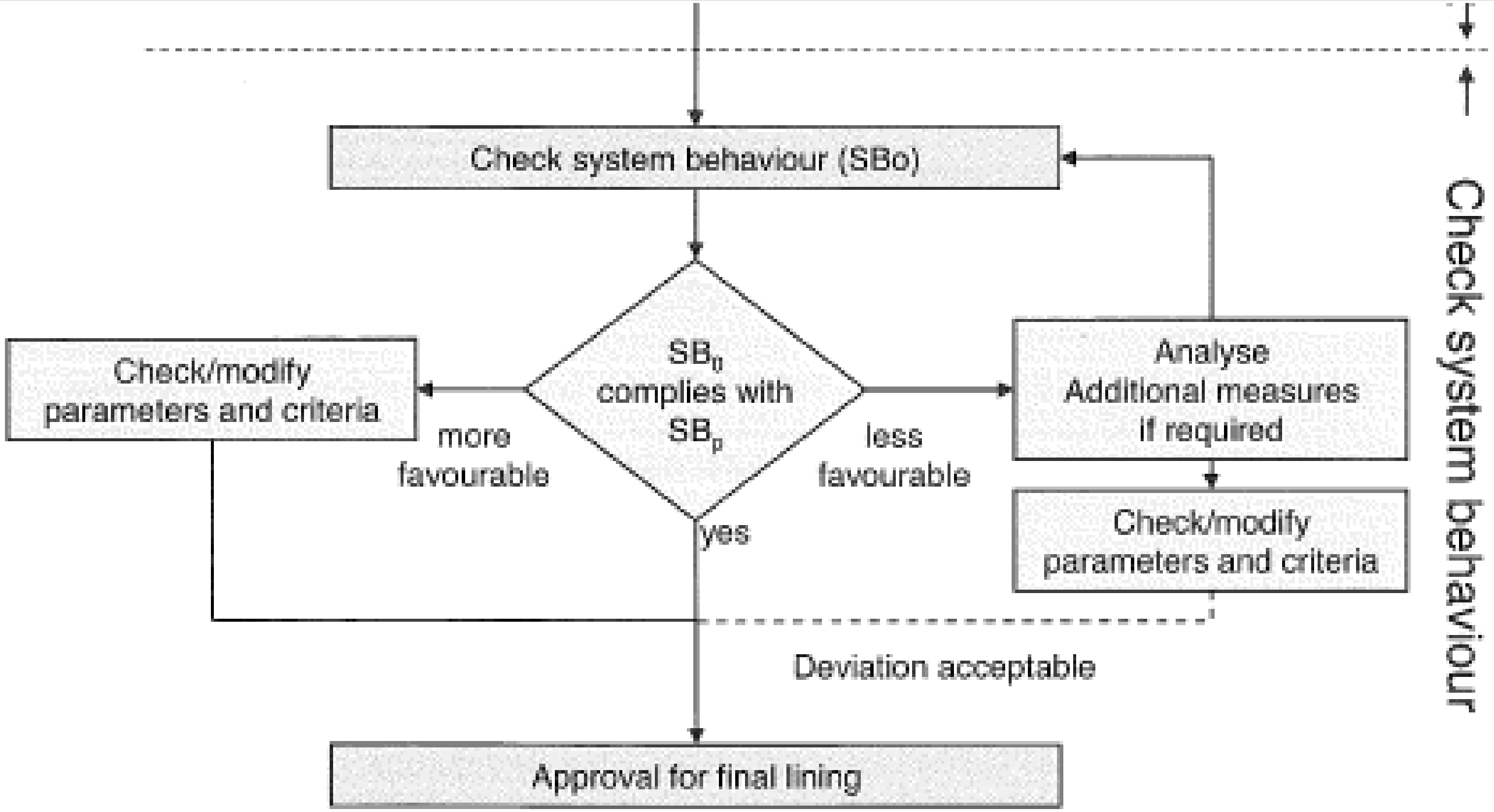
Specification, regulations for measurements and payment

Construction phase – selection of support



- Geological Documentation / Face Mapping as the main input
- Review of the Geotechnical Monitoring Data
- Any other data, e.g. probe drillings

Construction phase – "Feedback loop"



What types of feedback ?

- Geotechnical Monitoring
  - To observe the system behaviour
  - To monitor physical parameters and compare them to design values
- Geological documentation
  - Standard practise in tunnelling
  - Two objectives
    1. Document the ground condition for measurement
    2. Assess ground condition for support choice
  - And to verify and update the geological model !

Geotechnical Monitoring in NATM

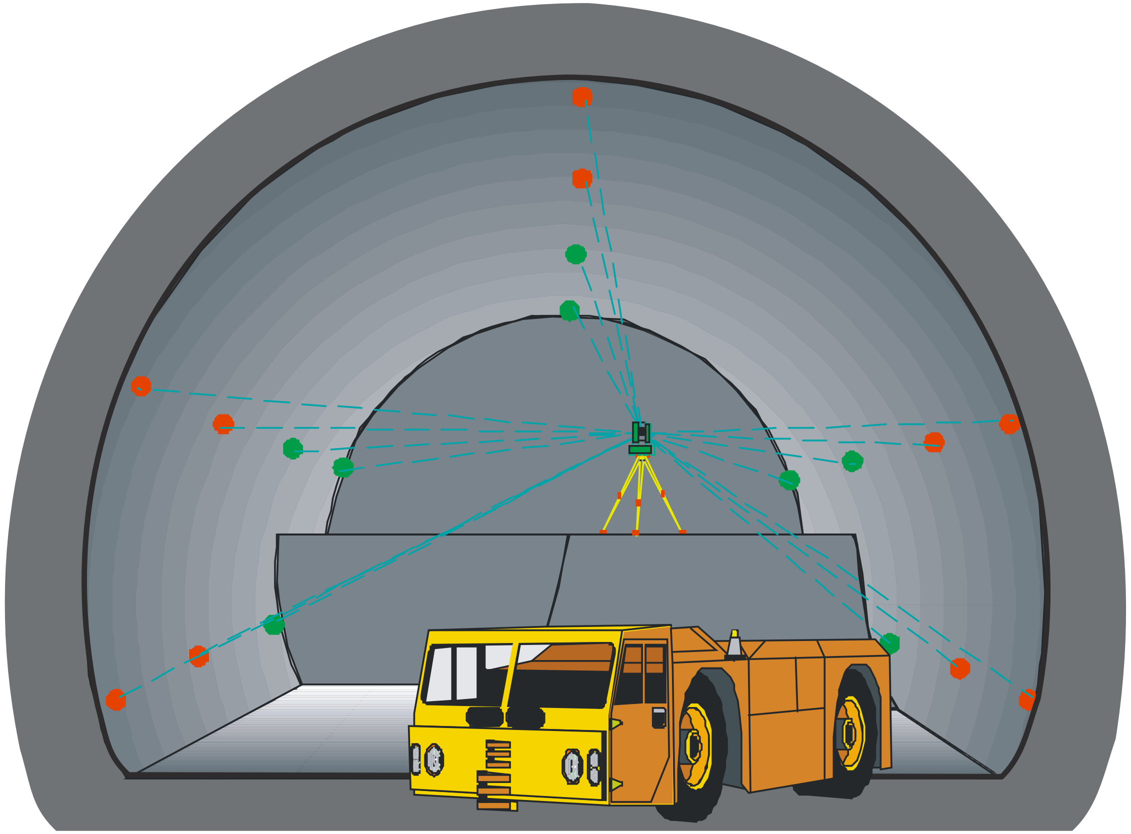
Observation by means of Geotechnical Monitoring is an integral part of NATM for

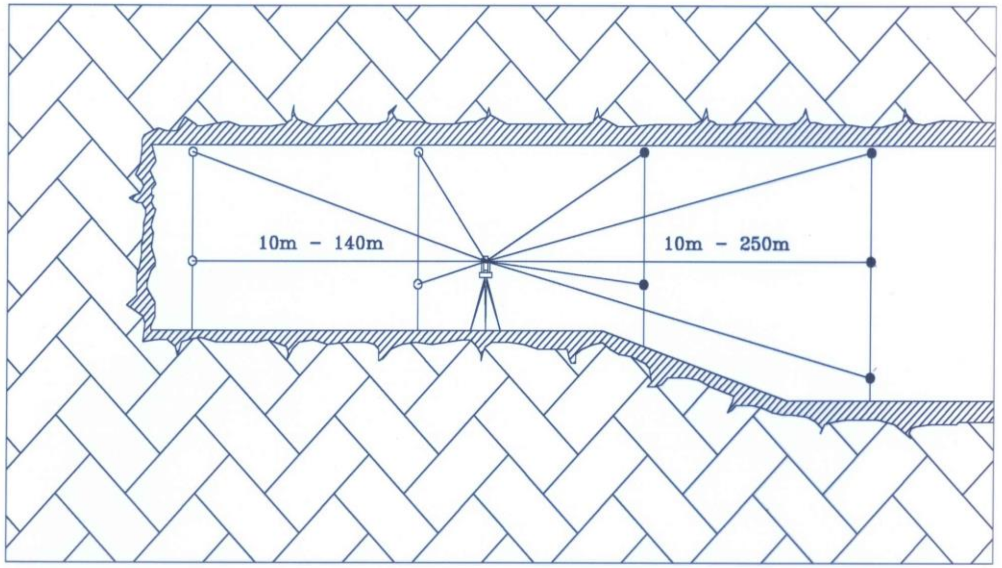
- Determination of stability
- Check of pre-dimensioning
- Identification of previously not anticipated behaviour
- Final dimensioning of support measures during construction
- Optimisation of support measures in relation to the allowable deformations
- Optimisation of construction processes

Geotechnical Monitoring

- Design Stage
  - Site investigations
  - In-situ tests for determination of ground behaviour
- Construction Stage
  - Monitoring of system behaviour
  - Verification of geological model and of geomechanical parameters
- Operation Stage
  - Stability control by means of critical value monitoring
  - Long-term monitoring

Optical Displacement Monitoring “Free Stationing”





Information Flow – GT Monitoring Software

Data Acquisition

↓

Data Processing

↓

Data Presentation

↓

Interpretation

Ideally the data cannot be manipulated after having been inserted into the database. Outlier can be switched on and off.

The software should be able to quickly produce standard graphs.

The graphical presentation of monitoring data is usually done in the following formats:

- Time displacement diagrams
- Vector diagrams
- Influence lines & trend lines
- Stereographical projection

Support Measures

- Objectives and Choices
- Constraints
- Implementation

Objectives for the Support Measures

- Avoid Loosening of Ground
- Build up support "pressure" to keep the ground in a triaxial stress state during load redistribution
- Seal the surface of the rock mass
- Endure the same deformations like the rock mass
- Follows the excavation geometry (which is seldom perfect)
- Constructability is a requirement

- KEEP THE UNDERGROUND CAVITY OPEN AND ENSURE THE STABILITY OF THE CAVITY

How to meet this Objectives ?

- Put in support as soon as possible
- Have a support with immediate strength
- Have a support which “strengthens” the ground
- Have a support bonded with the ground
- Have a support where the strength / thickness can be adjusted
- Have a ductile support, which can endure some deformations if deformations are allowable / required

Exemplary Questions

- Settlements are an issue ?
  - Deep tunnel – No
  - Shallow Tunnel – Yes, so overall support stiffness (also short term) is to be achieved
- Will the rock mass show squeezing ?
  - No – support can be designed to cater for short term displacement
  - YES – measures have to be taken to ensure that the support system keeps is <u>integrity</u> and stays <u>ductile</u>
- Is it fair to assume that there are time-dependent phenomena ?

Sprayed Concrete (SprC)

- Seals the ground, with two effects:
  - No loosening and falling out of blocks
  - Closing of fissures / cracks – stress peaks are reduced
- Bonds with the ground and immediately develops strength
- No issues in placing if there is geological overbreak or uneven surface occurring when using the natural material "rock mass"
- If necessary, thickness can be increased immediately
- If locally broken, repair is possible

Steel Ribs

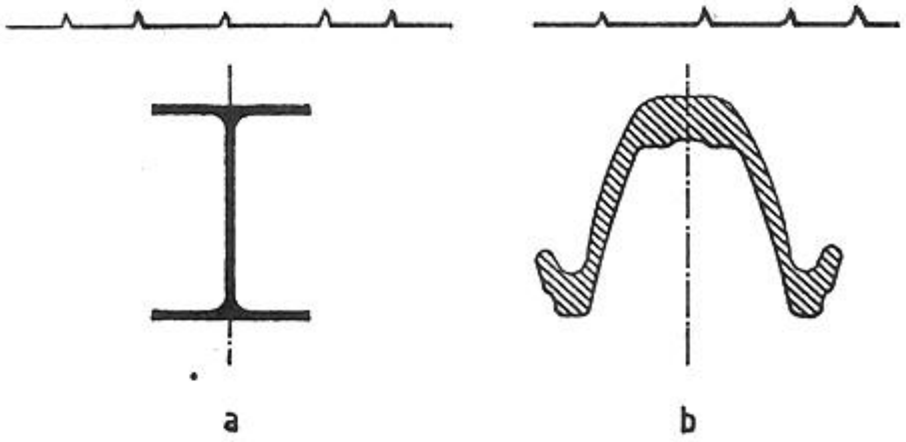
Desired function:

1. Structural impact confined to load distribution
2. Carrying of “green” shotcrete (?)
3. Profile control
4. Support for forepoling (?)

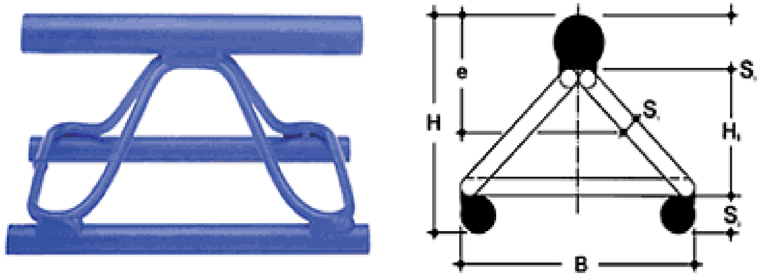
Old (Heavy) Types:

a) I or H beams

b) U-shaped bell profile (TH), for sliding connections:
   1) side wall galleries,
   2) deformation slots

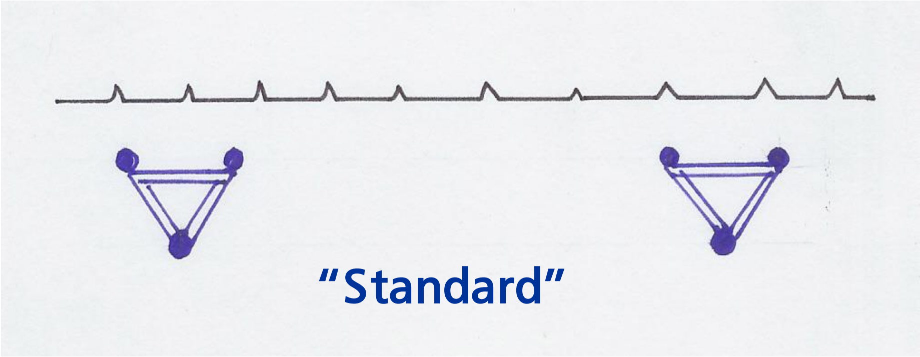


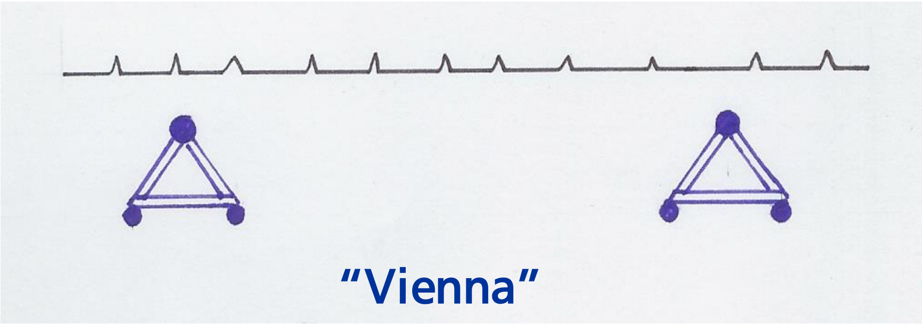
Steel Rib - Lattice Girder



PANTEX LATTICE GIRDERS

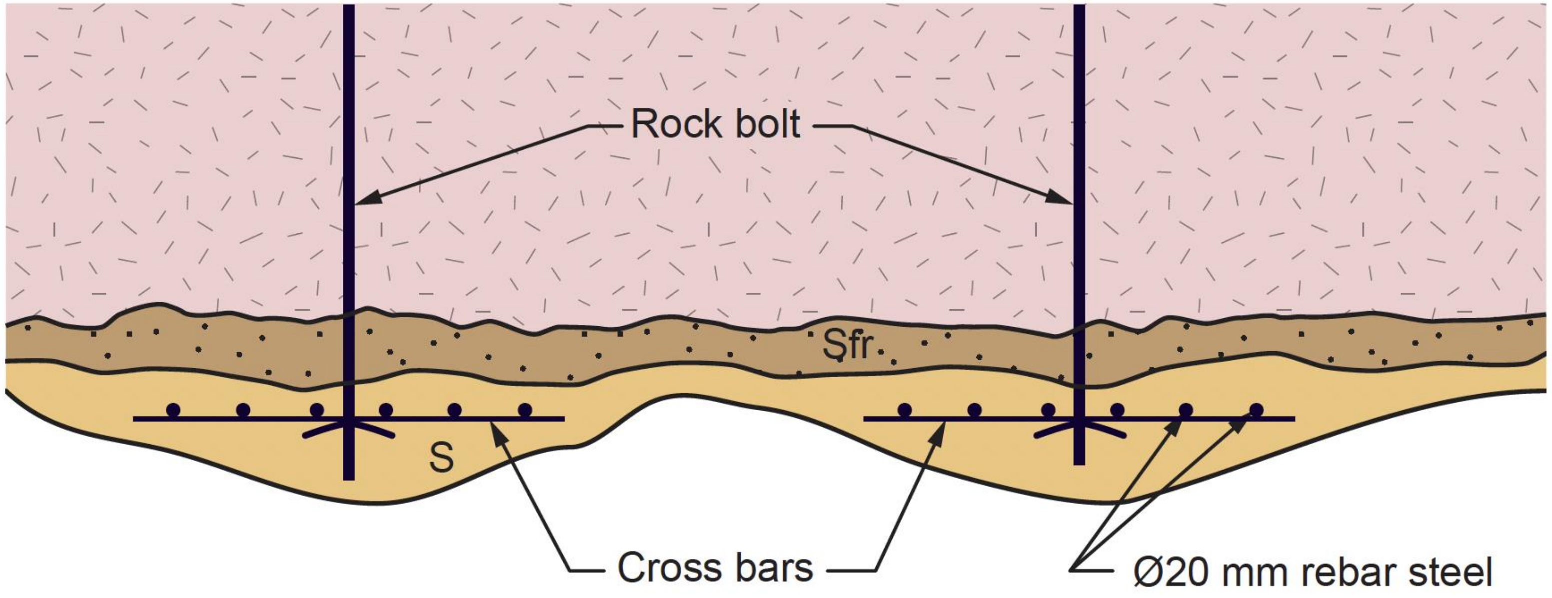
Layout Systems:



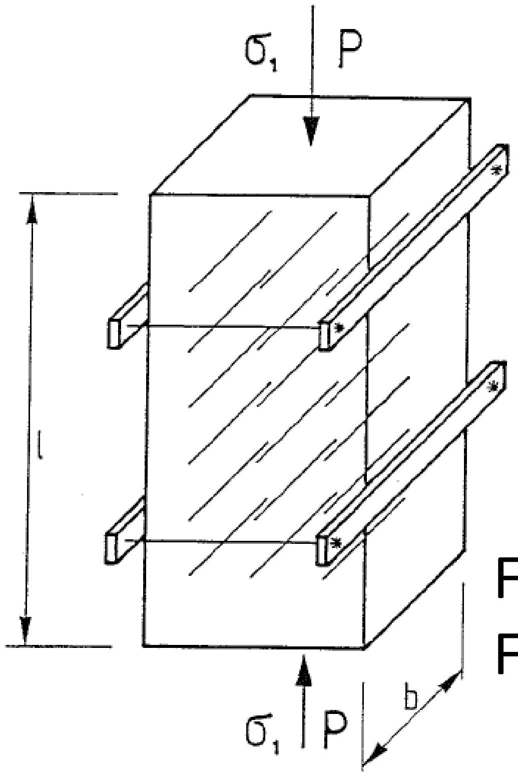


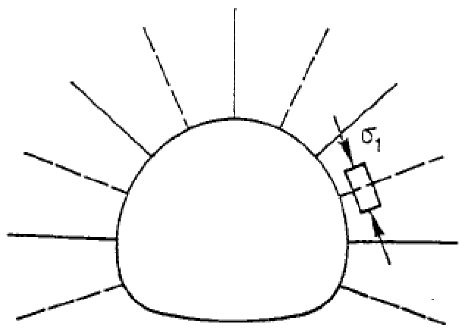
Reinforced ribs of sprayed concrete

- Proposed for very poor rock mass quality
- Range of application may be wider, to replace steel girders
- Rebar reinforced Sprayed Concrete

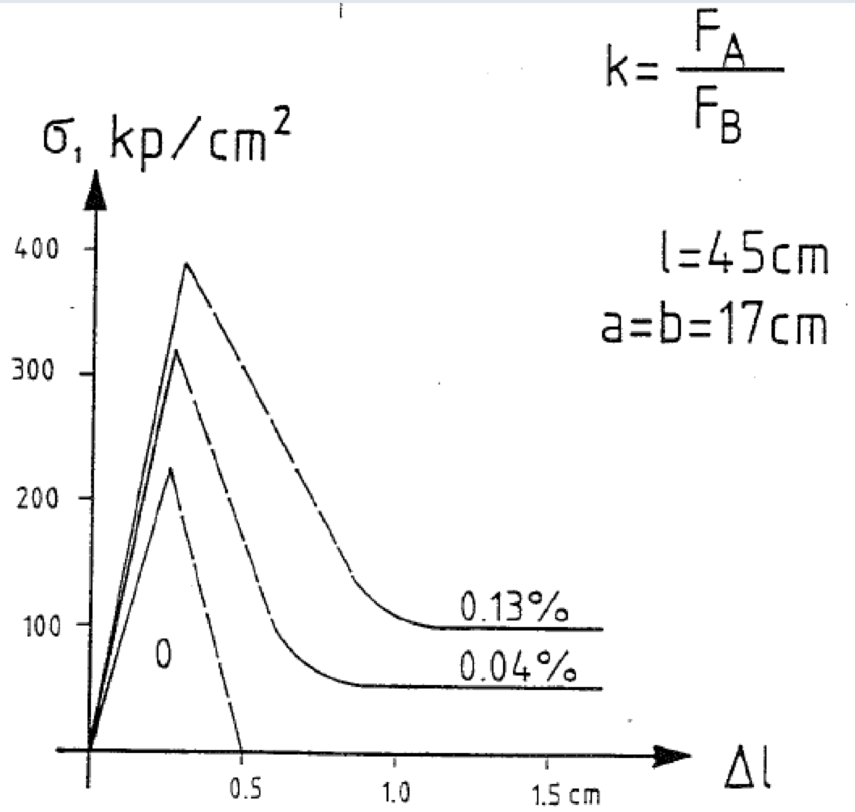


Rock Bolts – for the 3-dimensional stress state

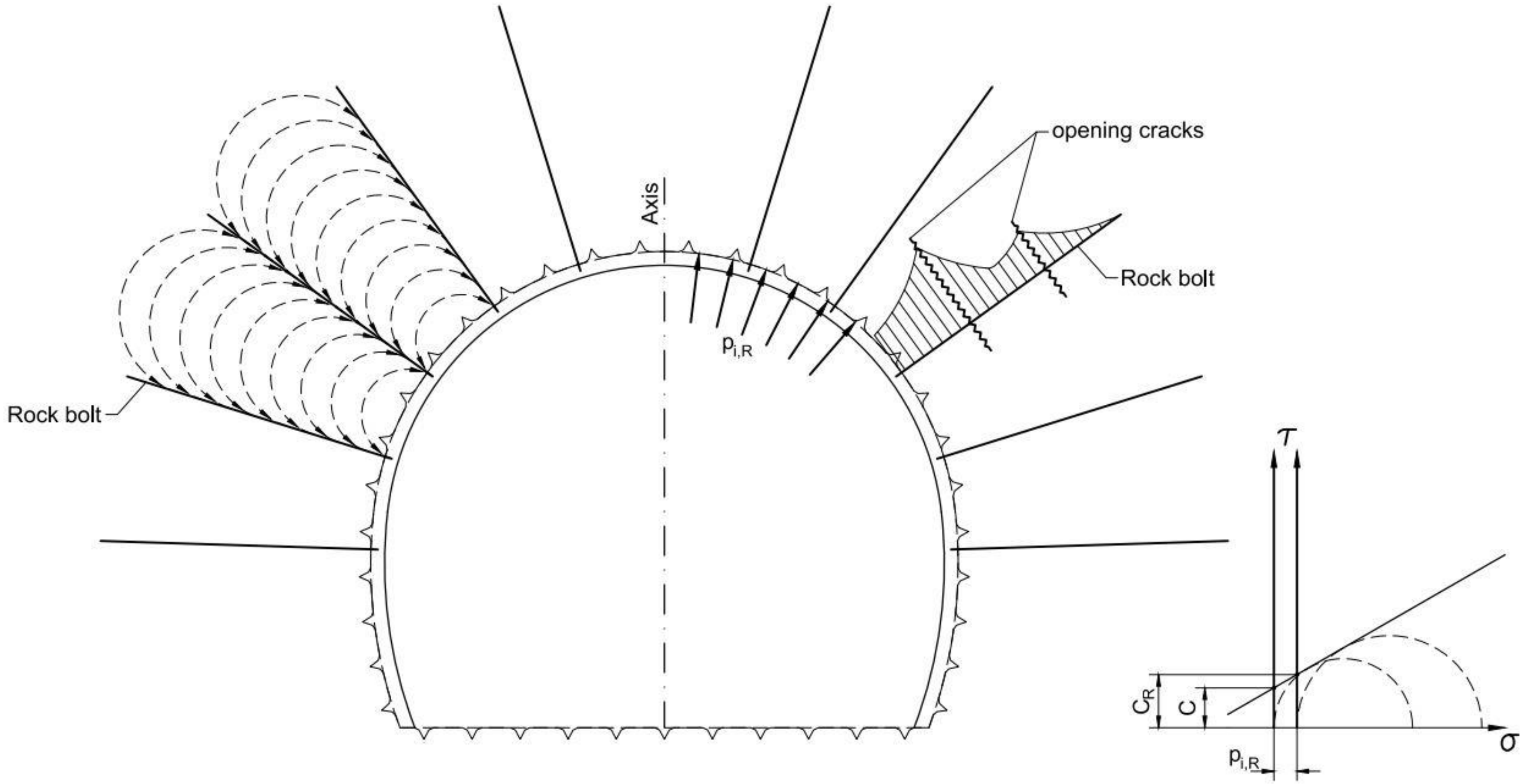




F_A = Bolt Area
F_B = Concrete Area

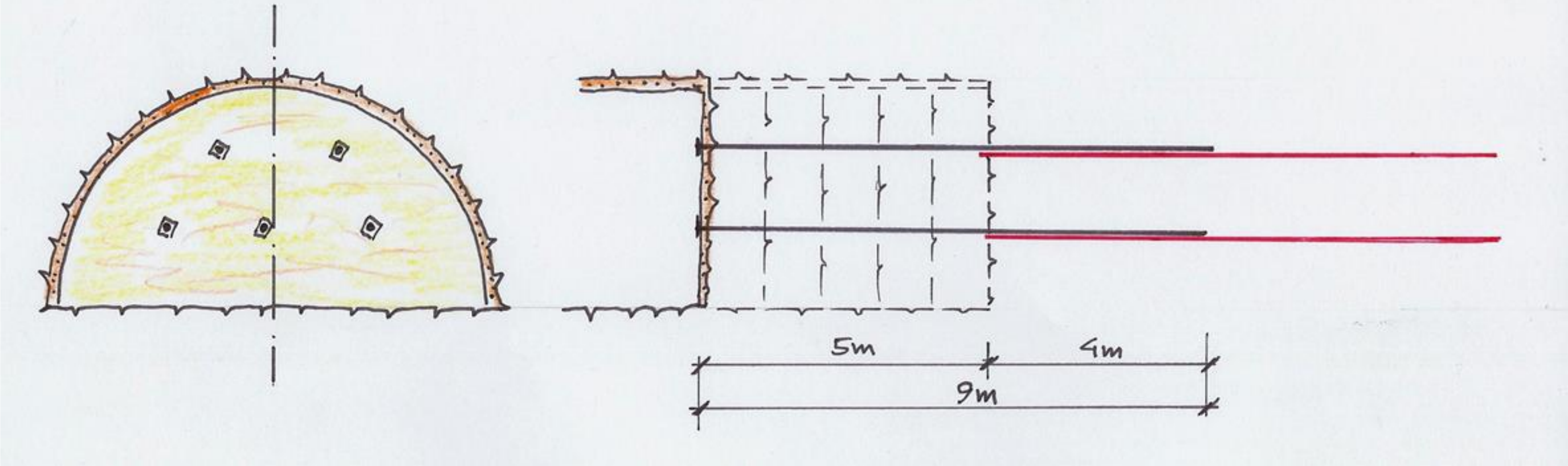


Fully grouted rock bolts



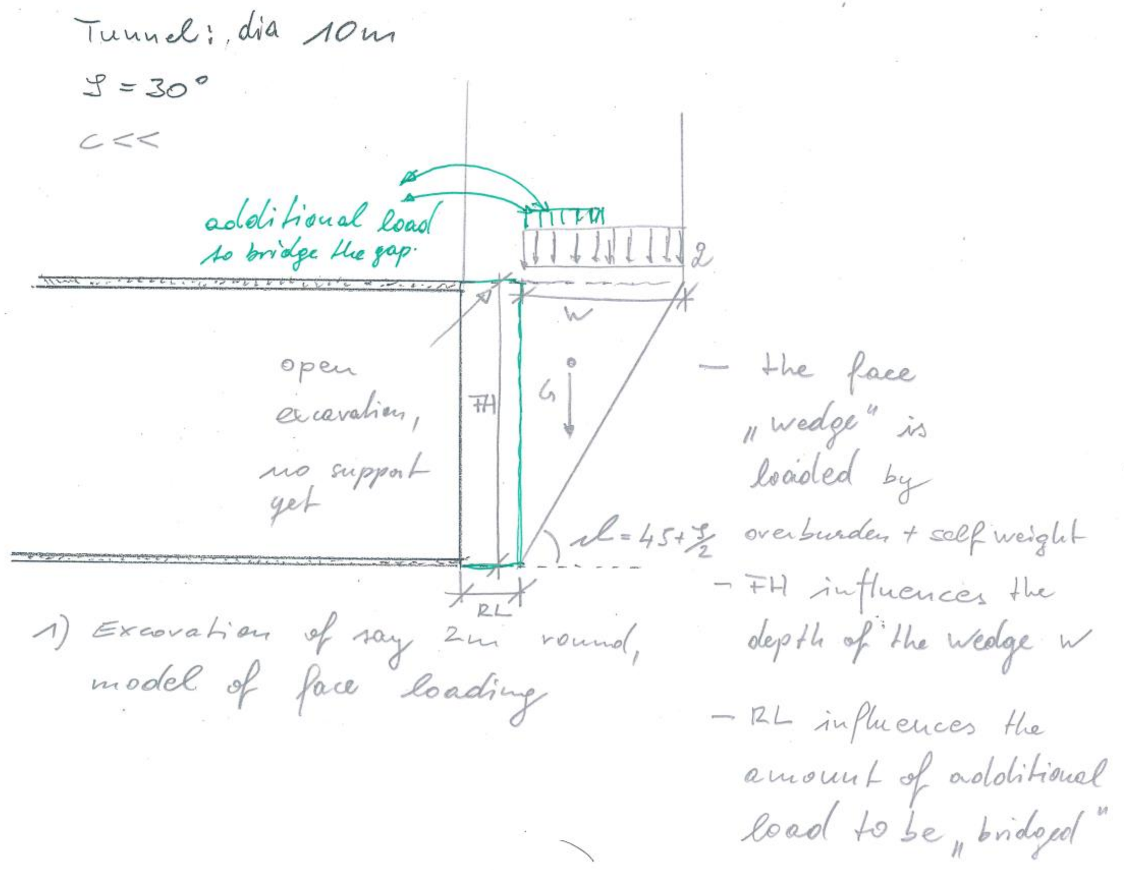
Face Bolts

Function: Stabilizing / supporting of the face.

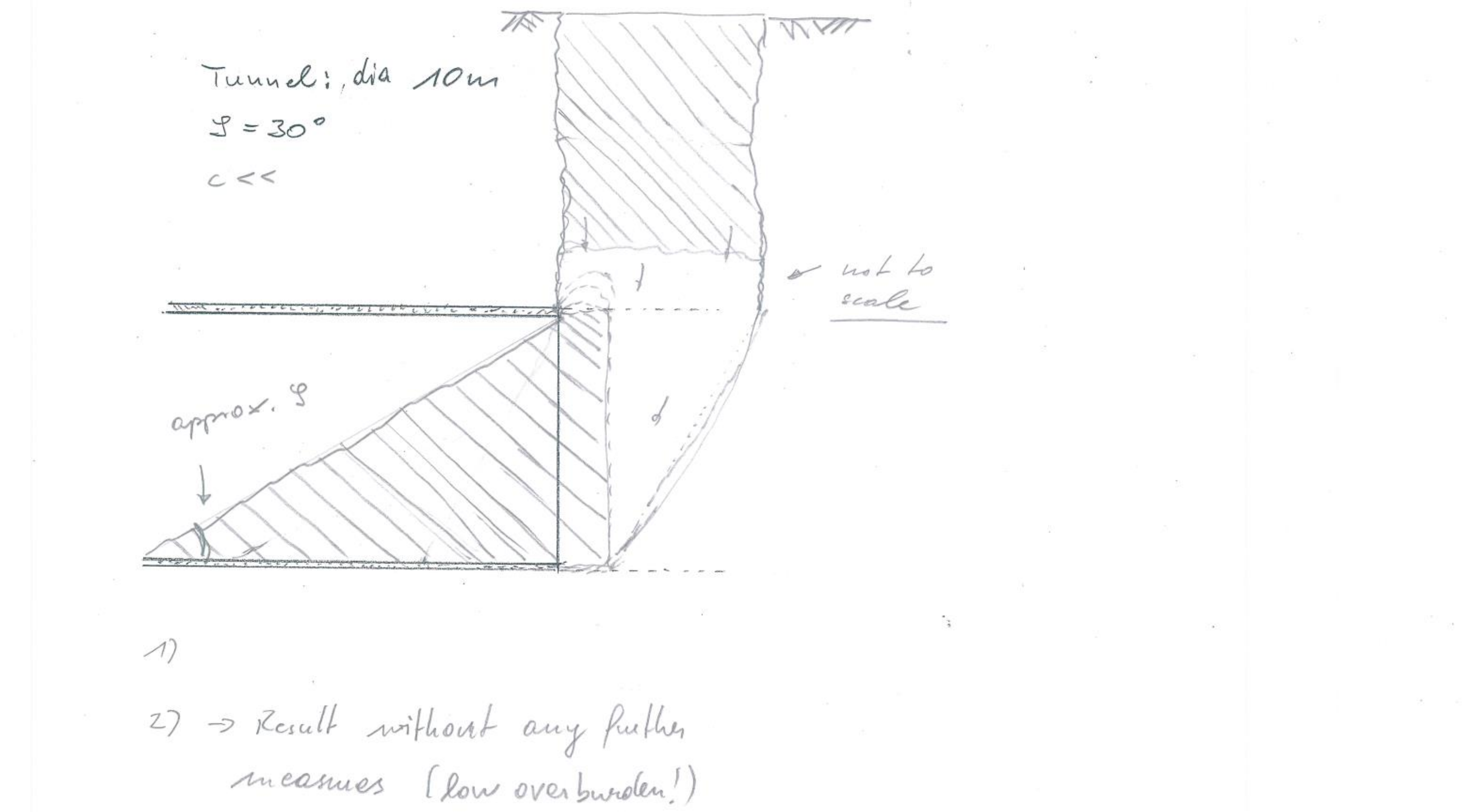


Application example - Top Heading – Bench

Design considerations – Shallow Tunnel 1



Design considerations – Shallow Tunnel 2

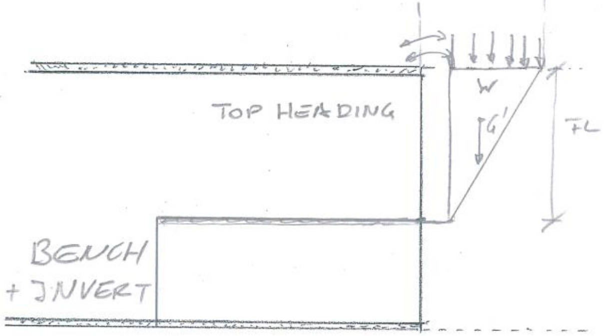


Design considerations – Shallow Tunnel 3

Tunnel: dia 10 m

$\varphi = 30°$

$c << $



Comparison:

$G = 10 \times 10 \times \tan(45 - \frac{\varphi}{2}) \times \frac{1}{2} \cdot \gamma = 50\gamma \tan 30°$

$G' = 6 \times 6 \times \tan 30° \times \frac{1}{2} \cdot \gamma = 18\gamma \tan 30°$

→ loading through overburden:

assume $q = 100\ kN/m^2$

$Q = 100 \times 10 \times \tan 30° = 1000 \tan 30°$

$Q' = 100 \times 6 \times \tan 30° = 600 \tan 30°$

if we assume $\gamma = 20\ kN/m^3$, then

$G + Q = 2000 \tan 30°$

$G' + Q' \doteq 960 \tan 30°$

(the load to be bridged is neglected here)

→ Measure:

- reduce round length RL to approx 1 m
- reduce face height FH to approx 6 m

Result: – W reduces
– additional load to be „bridged" reduces

Forepoling

Types:

- Pipes (diameter 1 ¼ – 1 ¾ inch)
- Rods (diameter ~32mm)
- Self drilling bolts (e.g. IBO)
- Lagging sheets

Installation:

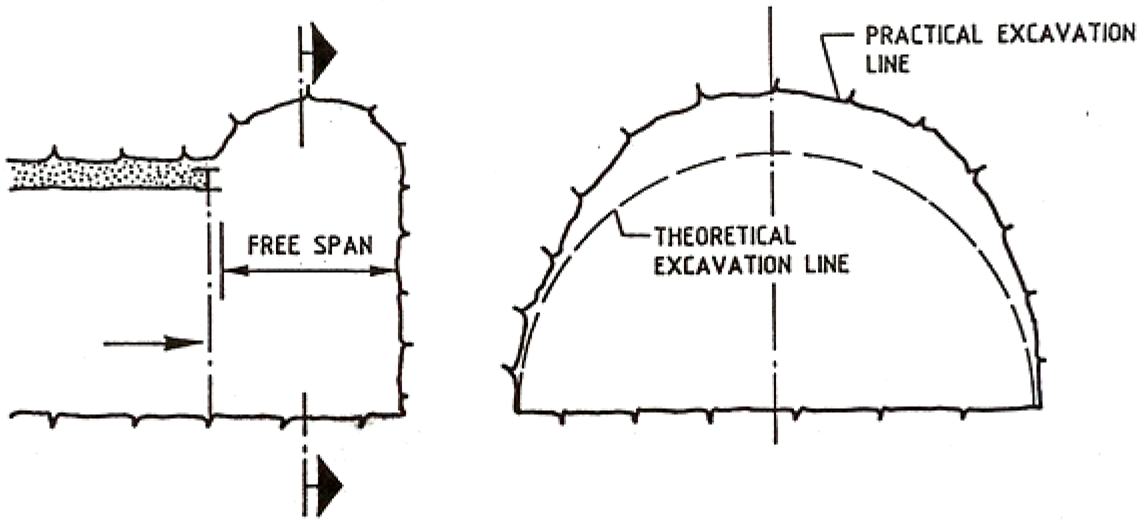
- Driven into the ground
- Installed into pre-drilled holes

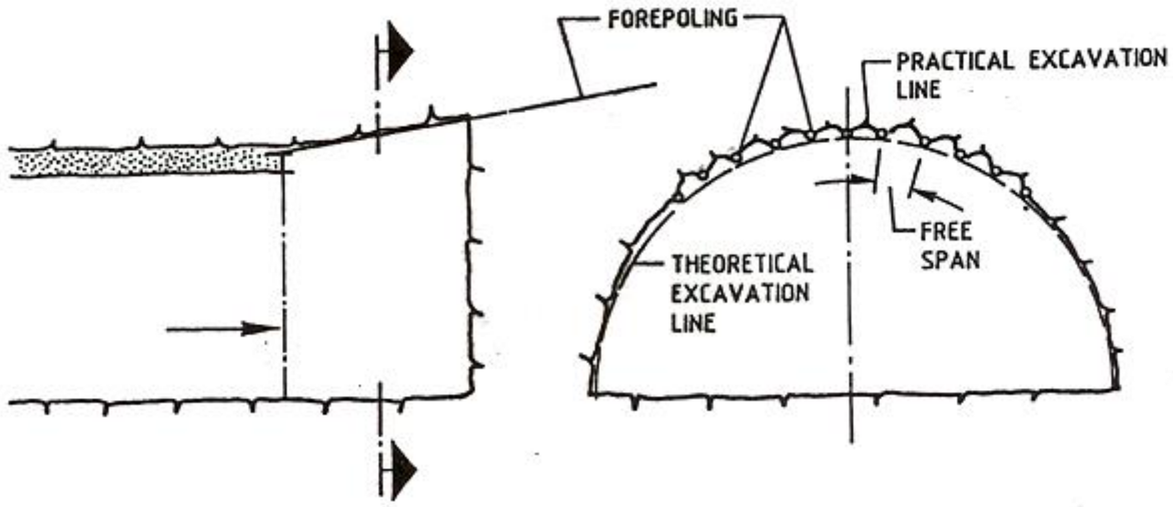
Objective

- Improvement of profile
- Avoid local caving in (with exponential growth !)
- In blocky material – keeping blocks in place
- Bridging the free span, especially in loose material

Forepoling

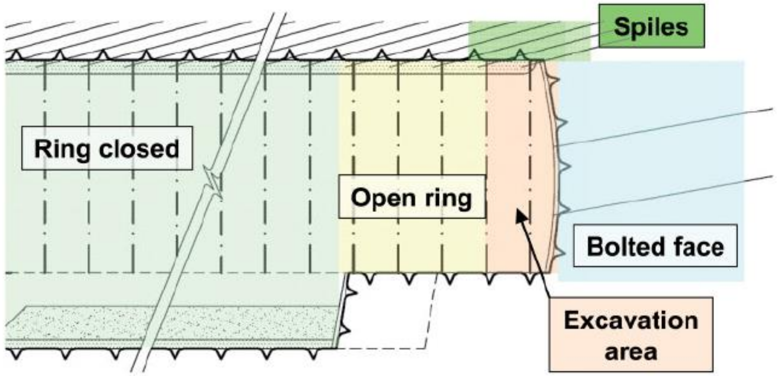
Shape of excavation ***without*** and *with* forepoling

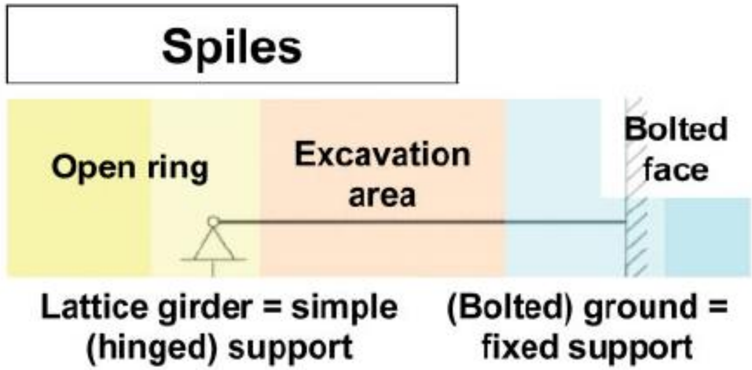


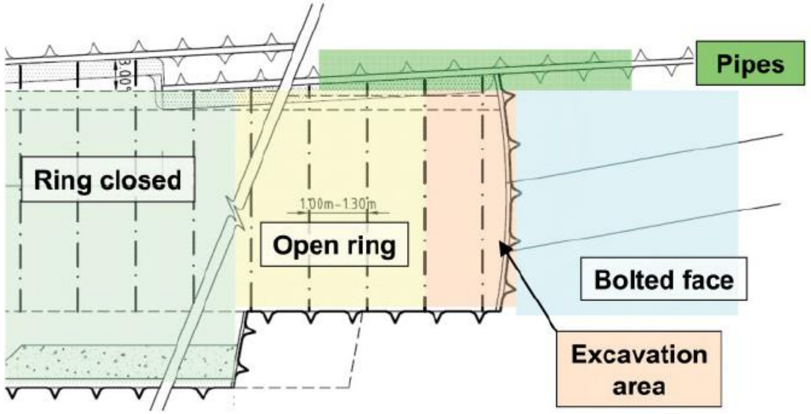


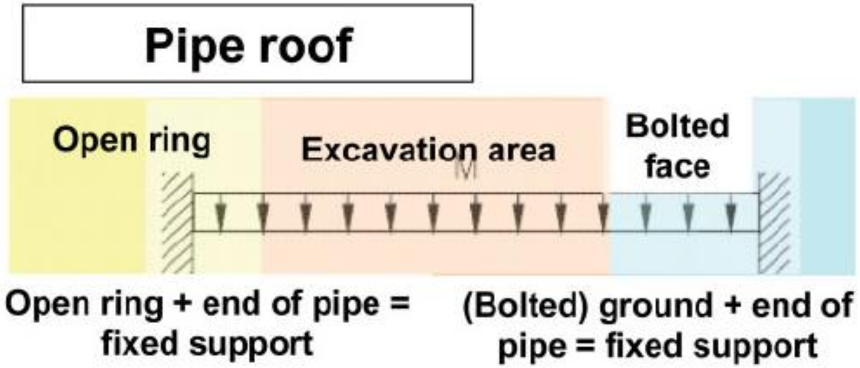
Pipe Roof – Pre-excavation measure

Different systems: Spiles – Pipe Roof

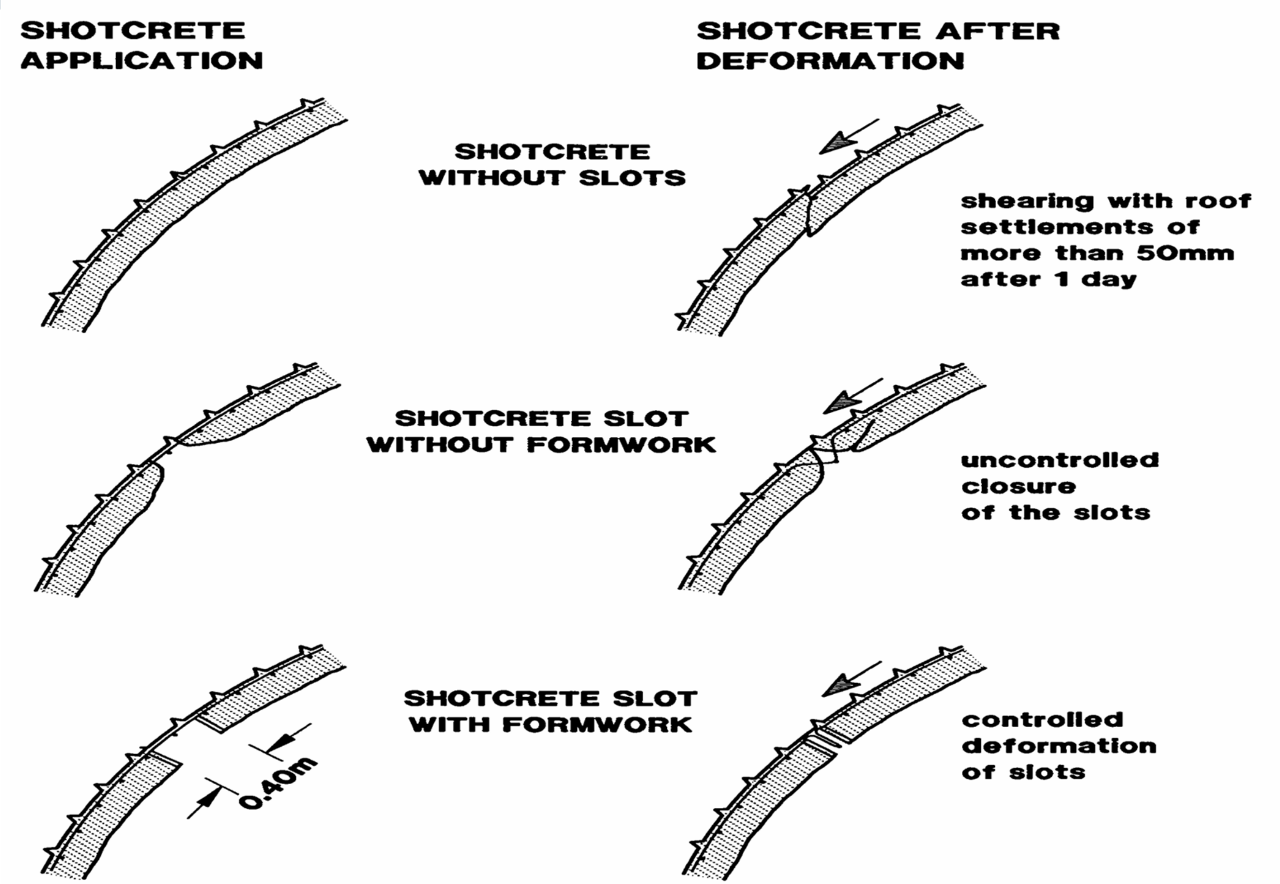






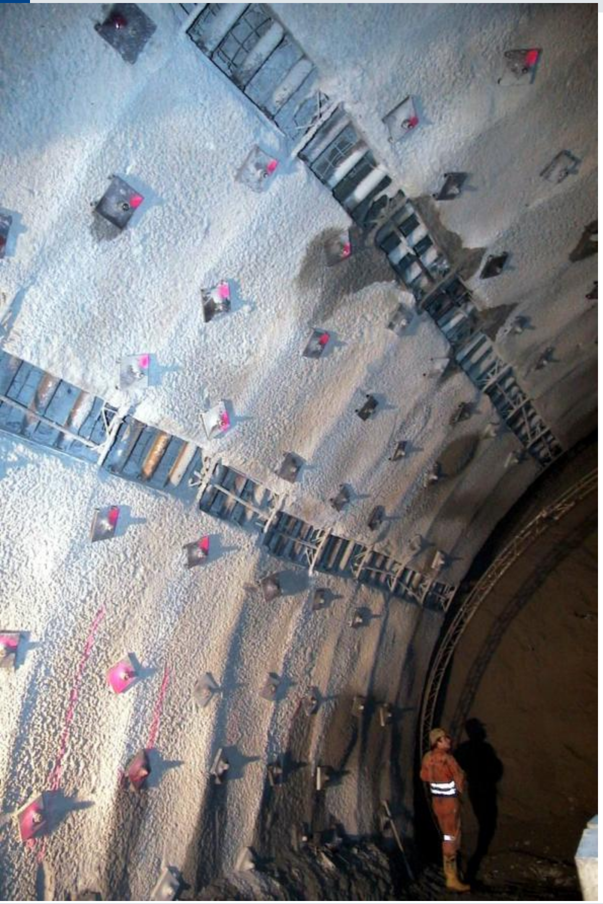


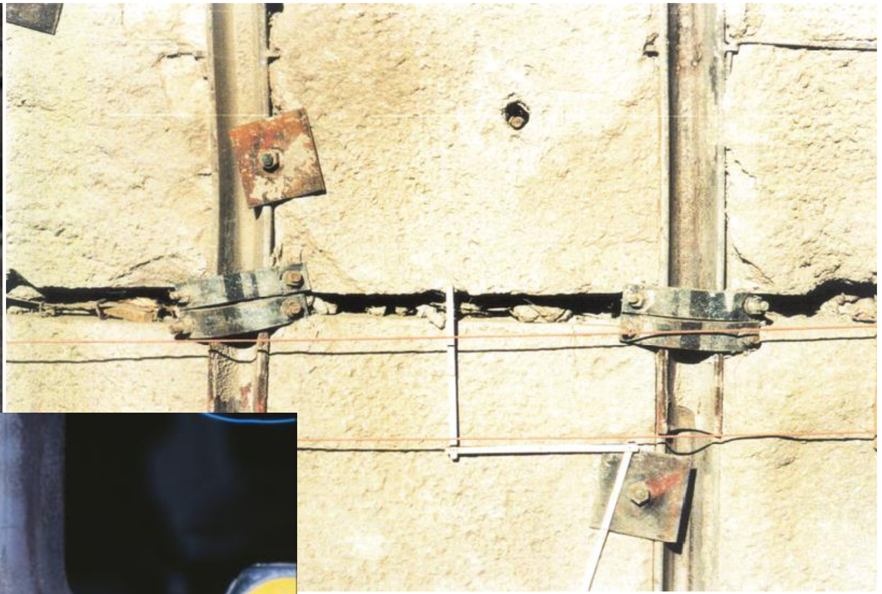
High deformation – sprayed lining slots



Lining Stress Controllers

Lining Stress Controllers 2

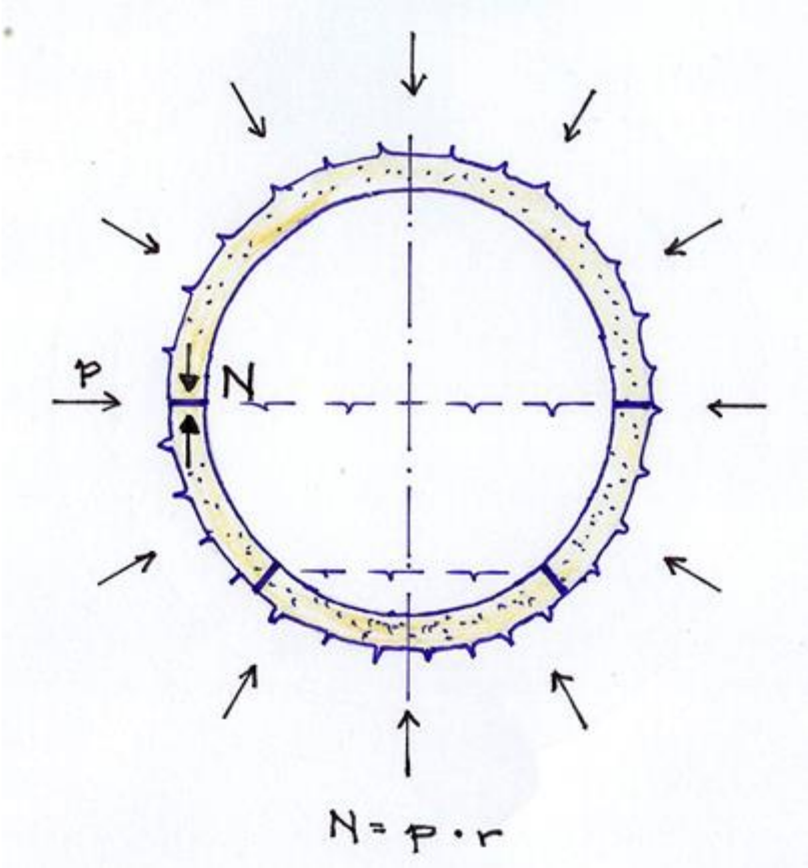




Constraints and Implementation Issues

- Sprayed Concrete
- Lattice Girders vs Steel Sets
- Rock Bolting
- Forepoling and Pipe Roofing

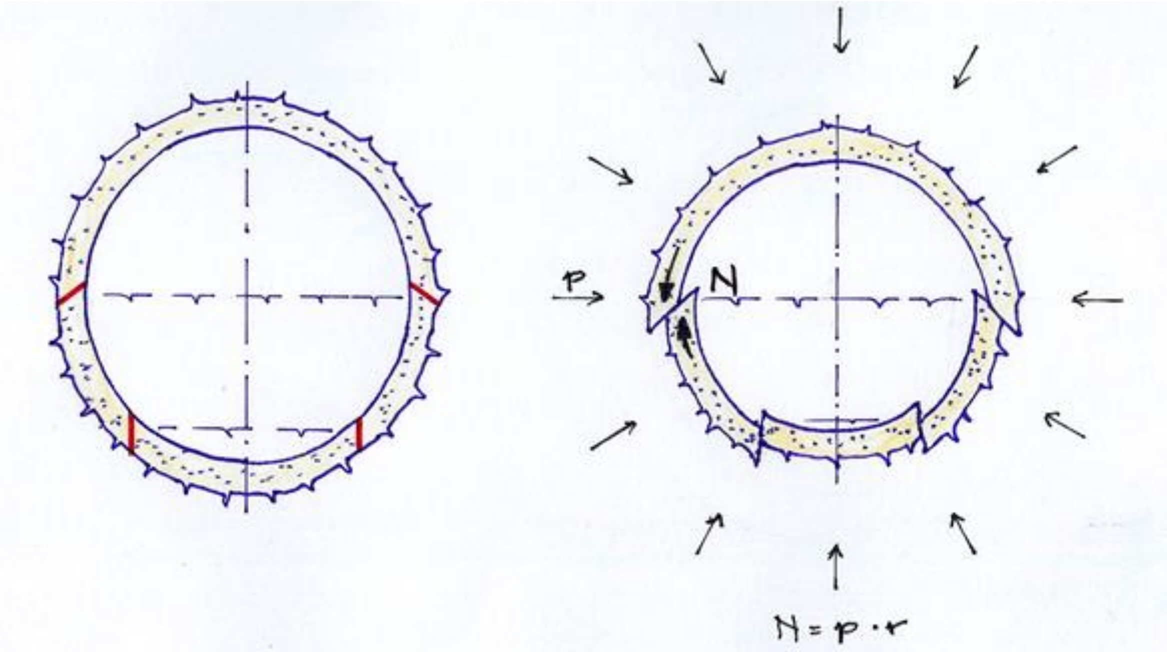
Sprayed Concrete - Joints



Radial Joints:

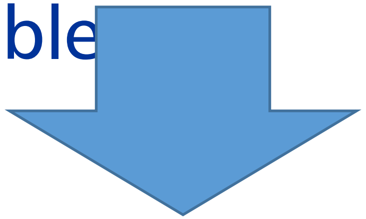
Transfer of lining normal force across the joints is possible.

Sprayed Concrete – Joints 2



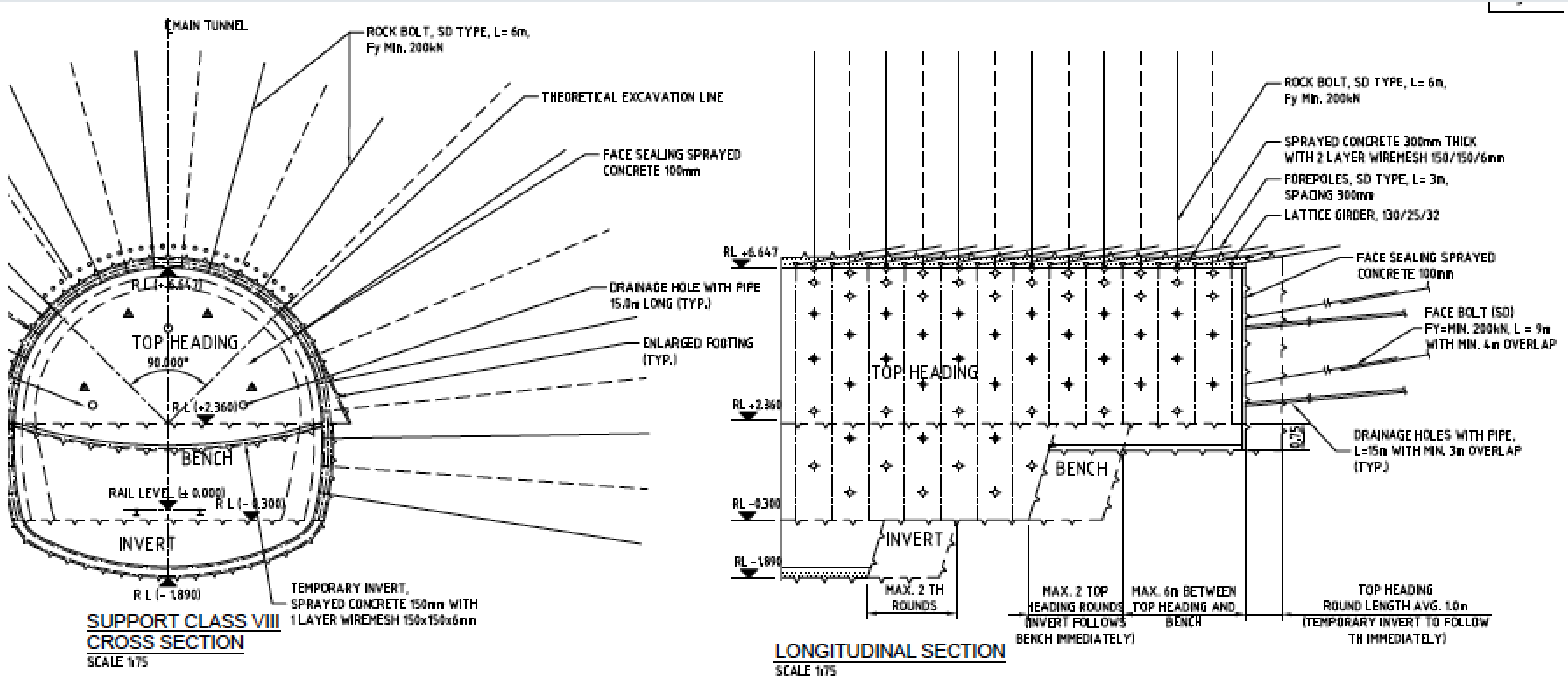
Non-Radial Joints:

Transfer of lining normal force across the joints is ***not*** possible

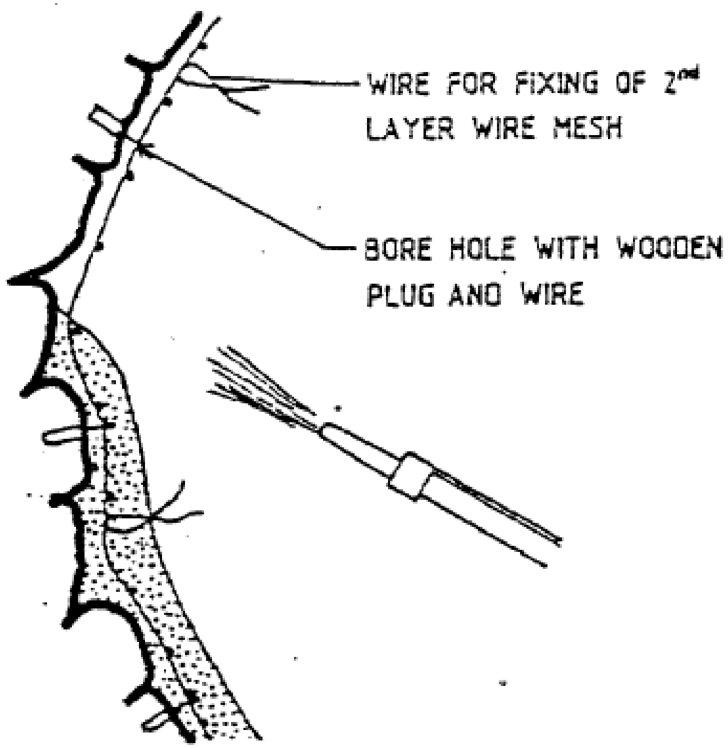


Unstable tunnel (collapse?)

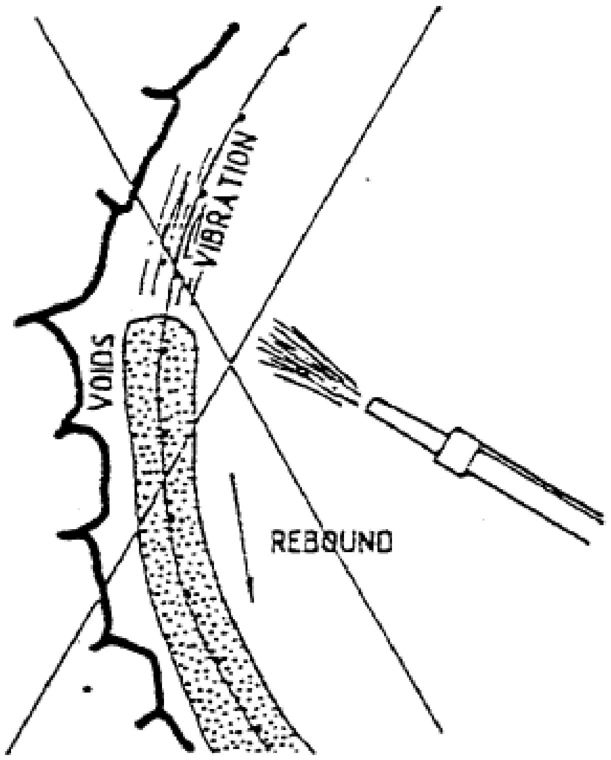
Example 1 – weak rock support class



Sprayed Concrete – implementation issue



PROPER FIXING



IMPROPER FIXING

Lattice Girder vs Steel sets

- LG is ideally embedded in Sprayed Concrete
- H-beam is hardly embedded, spraying shadows common
- Light weight – 14kg/m
- Heavy – ISHB150 27.1kg/m

Both are “stiffer elements” embedded in sprayed concrete – not always desirable, especially when voids occur due to spraying shadows (embedment lost).

Grouted Rock bolts – implementation issues

- Grout too thin – no proper annulus filling, bonding compromised
- Grouting happens too late – bonding compromised
- Grouting not done at all

↓

Not proper grouting means that a rock bolts degenerates to a piece of steel in the ground ….

Thanks for the opportunity and your attention !

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