SEQUENTIAL EXCAVATION IN SOFT GROUND AND HARD ROCK (OBSERVATIONAL APPROACH)

by

Dr. Rakesh Kumar (PhD IIT Delhi)

UV GLOBAL CONSULT

uvglobaldesign@gmail.com

INTRODUCTION

•**Sequential Excavation Method (SEM)**

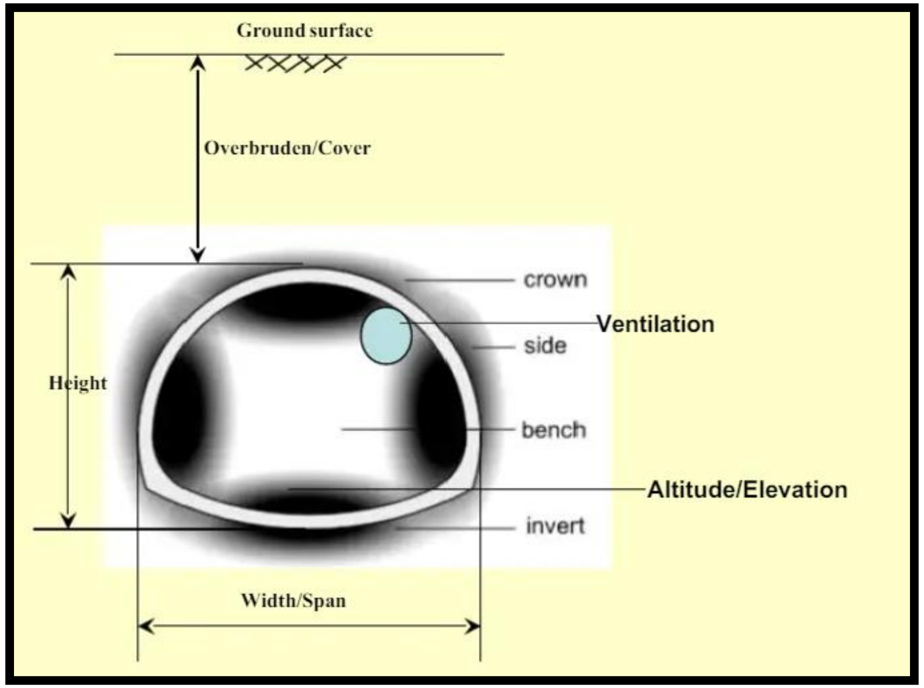
•Method of tunnel design and construction which started to gain popularity in the 1960s and 1970s. The essential component of the SEM approach is to take advantage of the **natural capacity and strength of surrounding rock/soil to support the tunnel** with minimum support system, cost and time

•**SEM and NATM**

•SEM is also known as the New Austrian Tunneling Method **(NATM)**. It can be said with some certainty that while there are similarities to SEM, the name **New Austrian Tunneling Method** was intended to distinguish it from the old Austrian tunnelling approach in the 1960s.

•**Sequential excavation** was well known when the term NATM was coined in 1964, and many believe that **SEM** was developed around 200 years ago by miners that had to adapt their techniques to the needs of civil engineering works. In his 1963 book entitled **"The History of Tunneling", Sandström** talks about the tunnelling methods devised in the first half of the 1800s

Basic Terms in Tunnels



INTRODUCTION

•**Basics of SEM**

•SEM tunnelling is characterized by the **sequential removal of ground material followed by the installation of support**. The SEM process includes a thorough investigation of the ground and adjacent structures to create functional **classifications** for **support** and **advance lengths** (maximum unsupported excavation length).

•Tunnel and geotechnical engineers use these classifications (or **pre-planned scenarios**) in combination with **direct ground observations** on-site to assess the result of the latest tunnel advance and **recommend new round length and class of support system** for the excavation operation ahead.

•In SEM, the **strength** of the ground around the excavation is purposely **mobilized** to the maximum extent possible. This is achieved by allowing **controlled deformation** using an initial primary support with load-deformation characteristics appropriate to the ground conditions.

INTRODUCTION

SEM Support System

•Timely **support installation** with respect to ground deformations and **monitored** by geotechnical instruments to assess developing deformations and make improvements to support selection for the work ahead.

•**Support measures** usually include **Shotcrete** and additional reinforcement as needed, such as wiremesh, lattice girders, bolts/SDA, or dowels in rock.

•Heading, bench, invert and side wall drifts depending on size of tunnel and geology

•In soft grounds of poor geological situations **pre-support measures** need to be used to **protect the next advance** before excavation and installation of support measures take place. Methods like spiling, forepoling, and pipe roofing/canopy, micropiling are among favourite techniques to improve the ground ahead.

•In SEM, rather than using stiff support members that attract high loads to fight the ground deformation, **flexible but strong** support measures (like shotcrete lining, wiremesh, bolts/anchors) are used to **redistribute** loads into the ground by **deflection** and allow the ground itself to become an integrated part of the tunnel support system.

INTRODUCTION: Loads and Ground Reaction Curves

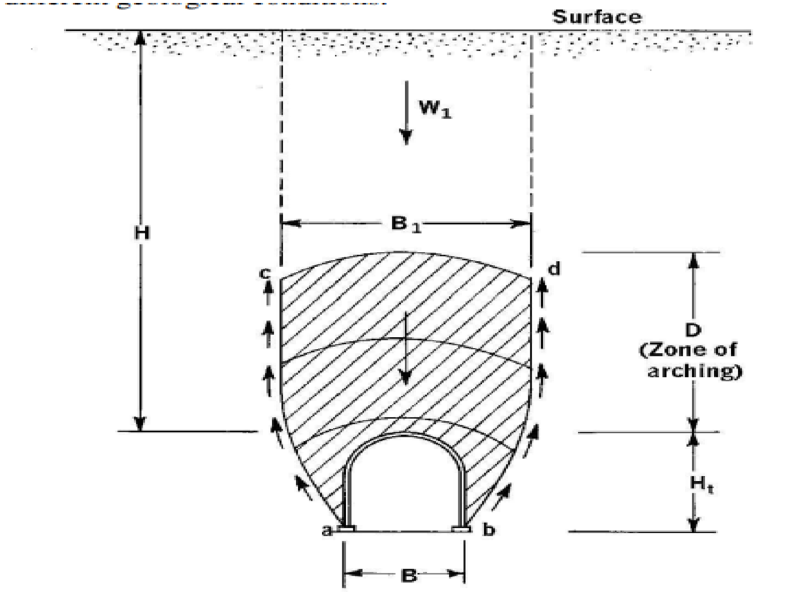
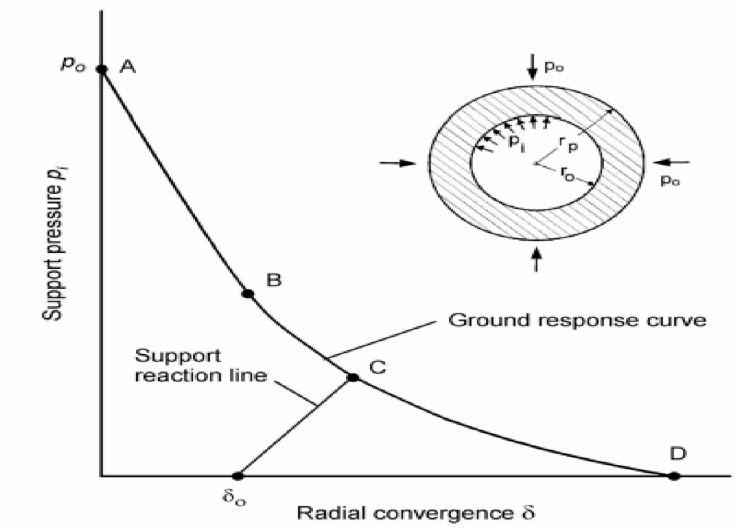


Fig. 1. – Terzaghi's ground arch concept. Reproduced from "Rock defects and loads on tunnel supports" published in 1946.

the radial convergence δ both increase as the support pressure decreases as illustrated in Fig. 2. Eventually, about two tunnel diameters behind the face, the support pressure p_i provided by the face has decreased to zero and the radial convergence δ reaches its final value.



Ground Considerations

•Another vital aspect of SEM is **ground classification systems**, which should be based on wide-ranging investigations and field observations. The **ground response** to tunnelling needs to be evaluated based on the data from the geological models in combination with the results from the investigation program and laboratory testing.

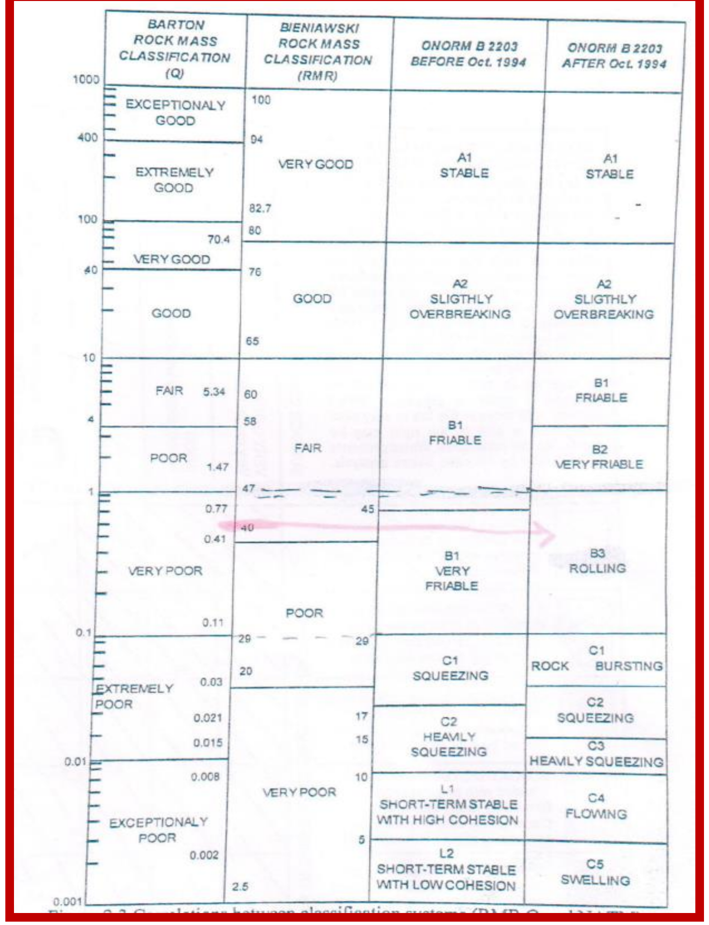
• These shall consider tunnel **size**, **shape**, **overburden height**, **groundwater** conditions, and **environmental** concerns.

• The next step is to calculate the **ground support** needs and plan for "excavation and support" **sequences**.

Ground Models/Characterisation, Rock Mass Type & Behaviour, Rock Support Type in SEM/NATM

Table 7-1 – Rock Mass Behaviour Types (Austrian Society of Geomechanics, 2010)

Rock Mass Behaviour Types (RMBT)	Description of potential failure modes/mechanisms during excavation of the unsupported rock mass
1 - Stable	Stable ground with the potential of small local gravity induced falling or sliding 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 faillure
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
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 stress relief
11 - Ground with frequently changing deformation characteristics	Combination of several behaviours with strong local variations of stresses and deformations over long sections due to heterogeneous ground (i.e. heterogeneous fault zones, block -in-matrix rock, tectonic mélanges)



Ground Models/Characterisation, Rock Mass Type & Behaviour, Rock Support Type in SEM/NATM

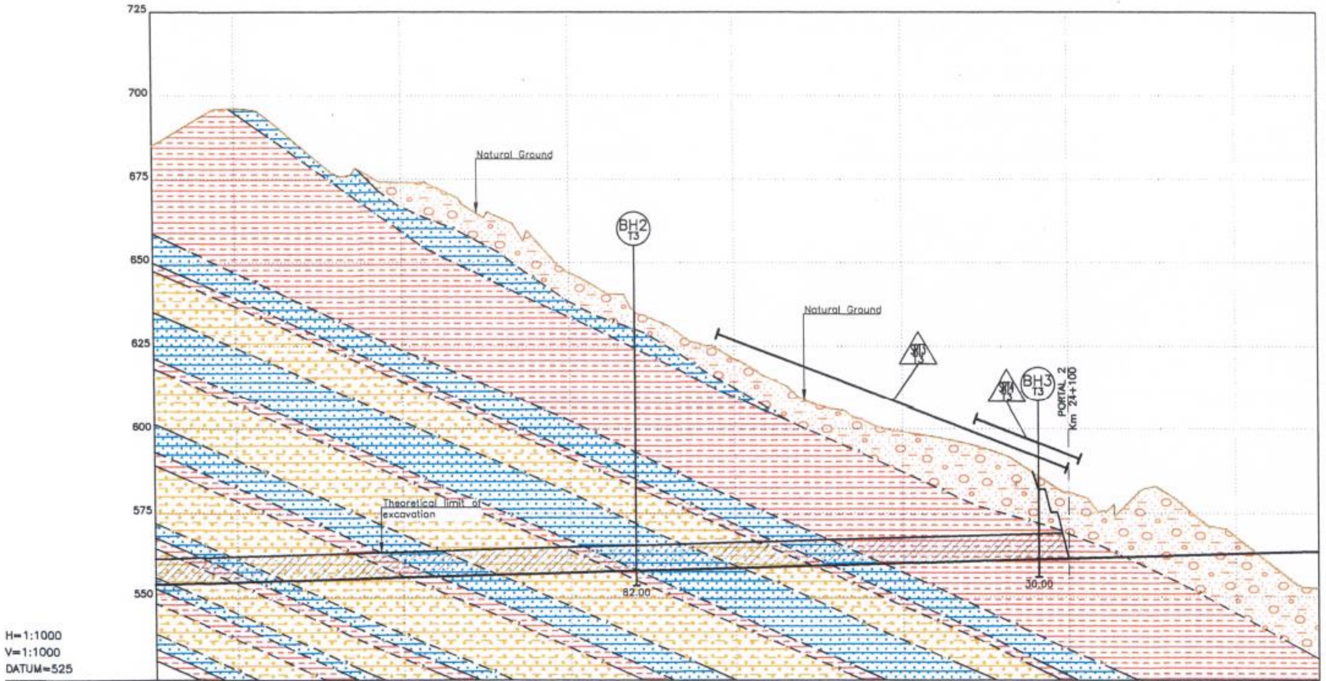
Rock Mass Behaviour Type (RMBT)	Geotechnical Zone (ZG)	Support Class (ONORM B 2203)	Description
RMBT 3/1	ZG1	A1 Stable	The rock mass behaves elastically. Deformations are small and decrease rapidly. There is no tendency of overbreaking after scaling of the rock portions disturbed by blasting. The rock mass is permanently stable without support.
		A2 Slightly Overbreaking	The rock mass behaves elastically. Deformations are small and decrease rapidly. A slight tendency of shallow overbreaks in the tunnel roof and in the upper portions of the sidewalls caused by discontinuities and the dead weight of the rock mass exists.
RMBT 3/2	ZG2	B1 Friable	Major parts of the rock mass behave elastically. Deformations are small and decrease rapidly. Low rock mass strength and limited stand-up times related to the prevailing discontinuity pattern yield overbreaks and loosening of the rock strata in tunnel roof and upper sidewalls if no support is installed in time.
		B2 Very Friable	This type of rock mass is characterised by large areas of nonelastic zones extending far into the surrounding rock mass. Immediate installation of the tunnel support, will ensure deformations can be kept small and cease rapidly. In case of a delayed installation or an insufficient quantity of support elements, the low strength of the rock mass yelds deep loosening and loaning of the inicial support. Stand-up time and unsupported span are short. The potencial of deep and sudden failure from roof, sidewalls and face is high.
RMBT 5/11	ZG3	C1 Squeezing	C1 is characterized by plastic zones extending far into the surrounding rock mass and failure mechanisms such as spalling, buckling, shearing and rupture of the rock structure, by squeezing behaviour or by tendency rock burst. Subject rock mass shows a moderate, but distinct time depending squeezing behaviour; deformations calm down slowly except in case of rock burst. Magnitude and velocity of deformations at the cavity boundary are moderate.
		C2 Heavily Squeezing	C1 is characterized by the development of deep failure zones and a rapid and a significant movement of the rock mass into the cavity and deformations wich decrease very slowly. Support elements may frequently be overstressed.
RMBT 8/11		L Loose Ground	No stand up time without support by prior installation of forepolling and shotcrete sealing of faces simultaeously with excavation.

TUNNEL BEHAVIOUR TYPES

Code	Description	Schematic	Photo
St	**Stable ground:** Stable tunnel section with local gravity failures. Rock mass is compact with limited and isolated discontinuities	St	
Br	**Brittle failure:** Brittle failure or rock bursting at great depths	Br	
Wg	**Wedge failure:** Wedge sliding or gravity driven failures. Insignificant strains. The rock mass is blocky to very blocky, blocks can fall or slide. The stability is controlled by the geometrical and mechanical characteristics of the discontinuities. The ratio of rock mass strength to the in situ stress (σ_{cm}/p_o) is high (>0.6-0.7) and there are very small strains (ε<1%)	Wg	
Ch	**Chimney type failure:** Rock mass is highly fractured, maintaining most of the time its structure (or at least that of the surrounded rock mass). Rock mass does not have good interlocking (open structure) and in combination with low confinement (lateral stress) can tend to block falls which develop to larger overbreaks of chimney type. The overbreaks may be stopped and "bridged" by better quality rock masses, depending on the in situ conditions. This type may be applied also in cases of brecciated and disintegrated rock mass in ground with high confinement (high lateral stress)	Ch	
Rv	**Ravelling ground:** The rock mass is brecciated and disintegrated or foliated with practically zero cohesion and depending on the intact rock interlocking (Rv1 case: without infilling) and possible secondary hosted geomaterial, (Rv2 case: with infilling, e.g. clay), rock mass can generate immediate rock mass ravelling in face and tunnel perimeter. The difference with Ch type lies in the block size, which is very small here, the self support timing, which is very limited here and the failure extension, where it is unrestricted due to the lack of better rock mass quality in the surrounding zone	Rv	
Fl	**Flowing ground:** The rock mass is disintegrated with practically zero cohesion and intense groundwater presence along the discontinuities. Rock fragments flow with water inside the tunnel	Fl	
Sh	**Shear failure:** Minor to medium strains, with the development of shear failures close to the perimeter around the tunnel. Rock mass is characterized by low strength intact rocks (σ_{ci}<15MPa) while the rock mass structure reduces the overall the rock mass strength. Strains develop either at a small to medium tunnel cover (around 50-70m) in case of poor sheared rock masses, or in larger cover in case of better quality rock masses. The ratio of rock mass strength to the in situ stress (σ_{cm}/p_o) is low (0.3<σ_{cm}/p_o <0.45) and strains are measured or expected to be medium (1-2.5 %)	Sh	
Sq	**Squeezing ground:** Large strains, due to overstressing with the development of shear failures in an extended zone around the tunnel. Rock mass consists of low strength intact rocks while the rock mass structure reduces the overall rock mass strength. The ratio of rock mass strength to the in situ stress (σ_{cm}/p_o) is very low (σ_{cm}/p_o <0.3) and strains are measured or expected to be >2.5%, and they can be also take place at the face	Sq	
Sw	**Swelling ground:** Rock mass contains a significant amount of swelling minerals (montmorillonite, smectite, anhydrite) which swell and deform in the presence of groundwater. Swelling often occurs in the tunnel floor when the support ring is not fully closed	Sw	
San	**Anisotropic strains:** The rock mass is stratified or schistose or consists of specific weak zones and develops increased strain characteristics along a direction defined by the schistosity.	San	

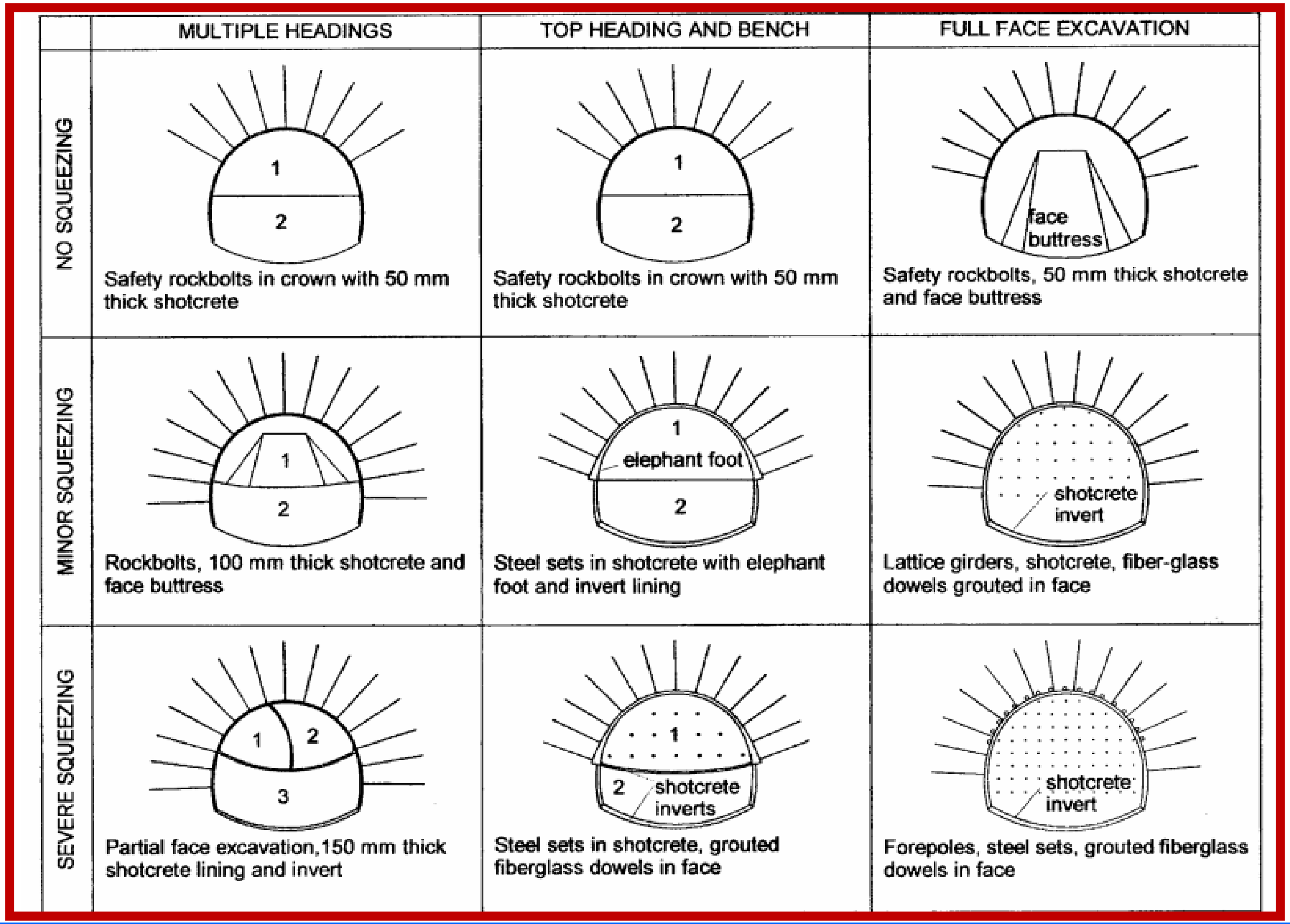
Fig. 11 Schematic diagram of tunnel behavior after Marinos [31]

Typical Ground Model and Geological L section

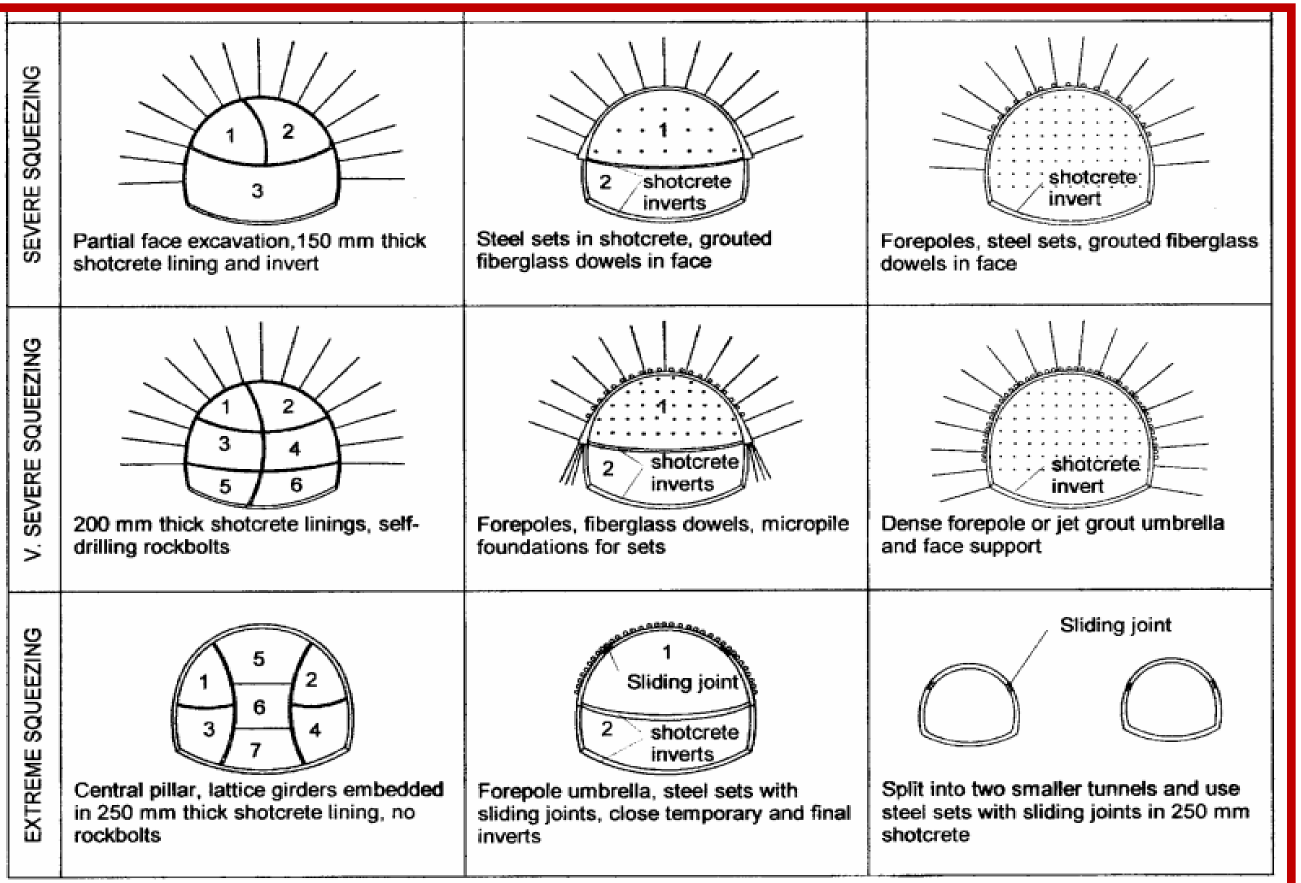


		23+850	23+900	23+950	24+000	24+050	24+100	24+150
GEOMETRIC ELEMENTS	ROAD LEVEL	554.388	555.814	557.240	558.666	560.091	561.517	562.943
	GROUND LEVEL	696.250	674.115	647.172	621.317	599.867	581.427	568.210
	OVERBURDEN	115 – 135	95 – 135	50 – 95		25 – 50	12–>25	
GEOTHECNICAL CLASSIFICATION	RMBT (ROCK MASS BEHAVIOUR TYPE)	3/1 – 3/2	3/1 – 3/2	3/1 – 3/2		3/2 – 5/11	8/11	
	SUPPORT SYSTEM	A2 (15%), B1 (45%), B2 (40%)	A2 (15%), B1 (45%), B2 (40%)	A2 (25%), B1 (45%), B2 (30%)		B1 (30%), B2 (30%), C1 (40%)	L	
	GEOTHECNICAL ZONE	ZG1/ZG2	ZG1/ZG2	ZG1/ZG2		ZG2/ZG3	ZG3	

Various Methodologies for SEM/NATM-Hard and Soft Ground



Various Methodologies for SEM/NATM-Hard and Soft Ground



Numerical Analysis

•In most design efforts for SEM, a **numerical model** of the tunnel and support systems is constructed using a **2D** or **3D finite element** (FE)/FDM/DEM program for soil and rock applications.

• FEM/FDM/DEM software can be used for a wide range of tunneling and underground projects to **simulate the complex interaction between ground and structural elements** and generally facilitates the excavation design and evaluation of support systems, groundwater seepage, consolidation, dynamic analysis, and much more.

Numerical Models for Hard Ground and Soft Ground

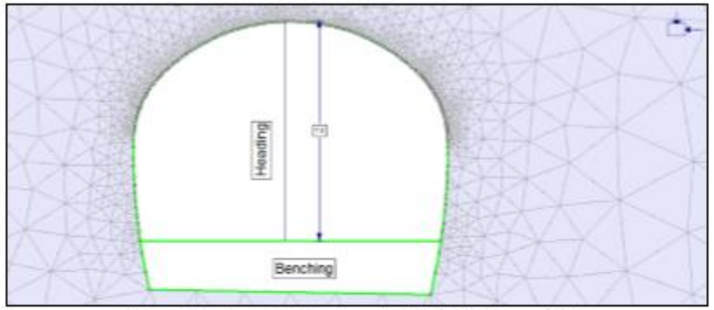


Figure 11: Discretization Boundary for Rock Classes I-IV

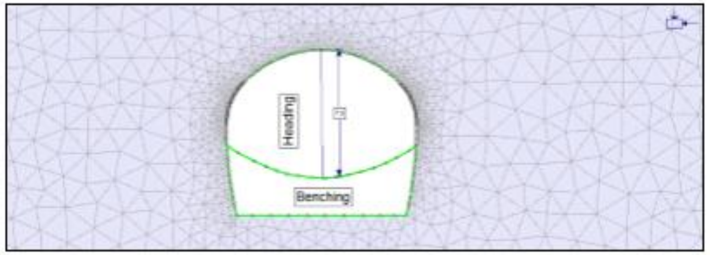


Figure 12: Discretization Boundary for Rock Class V

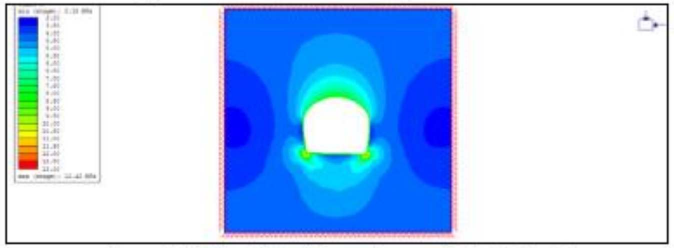
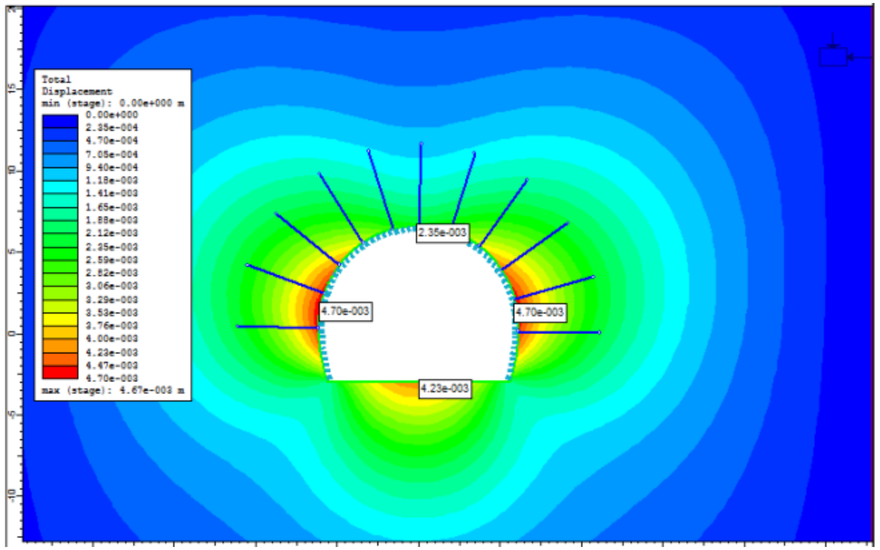
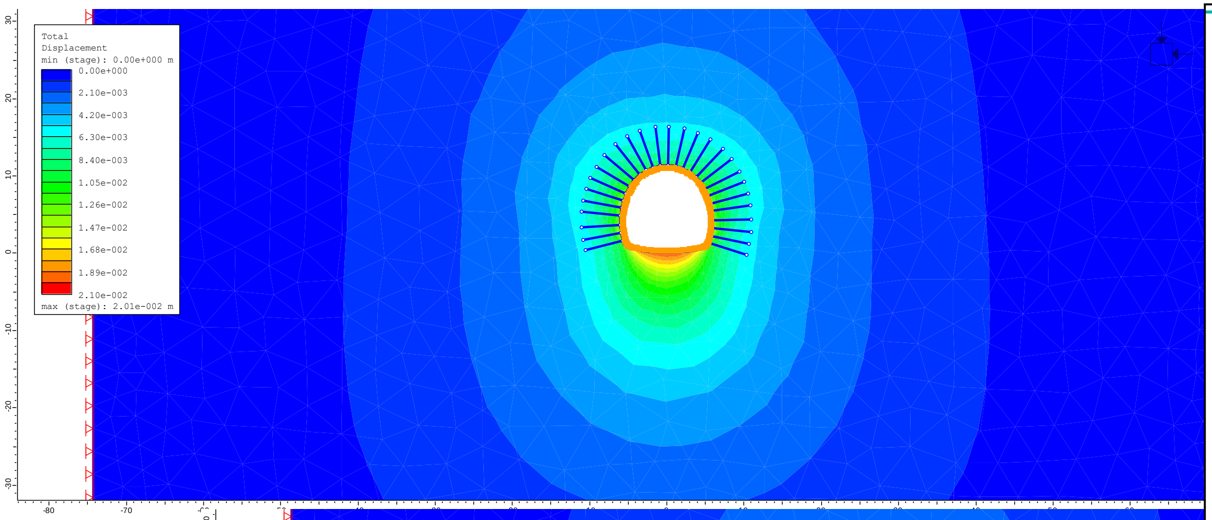
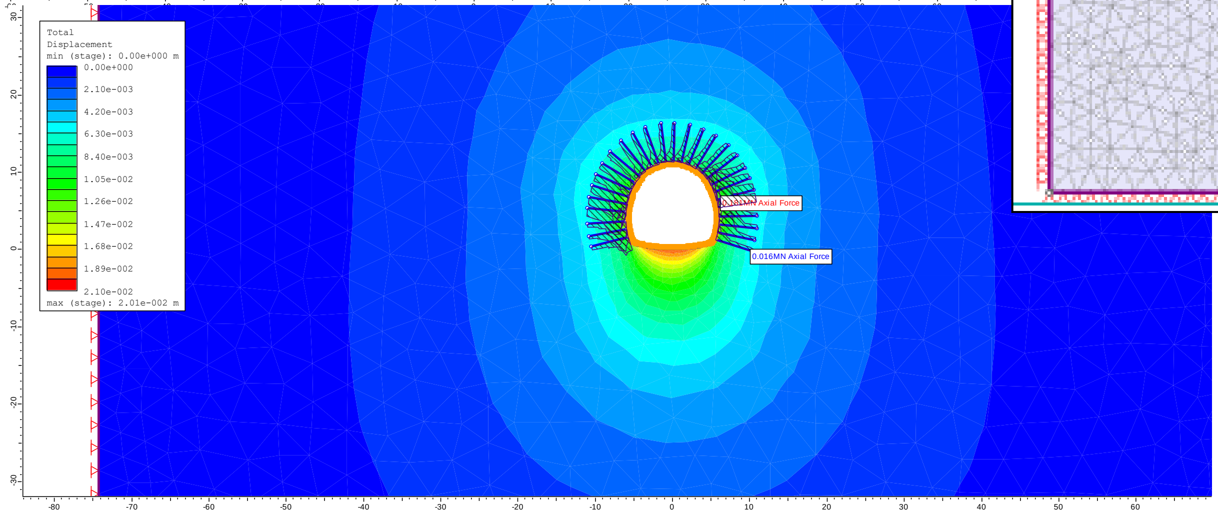


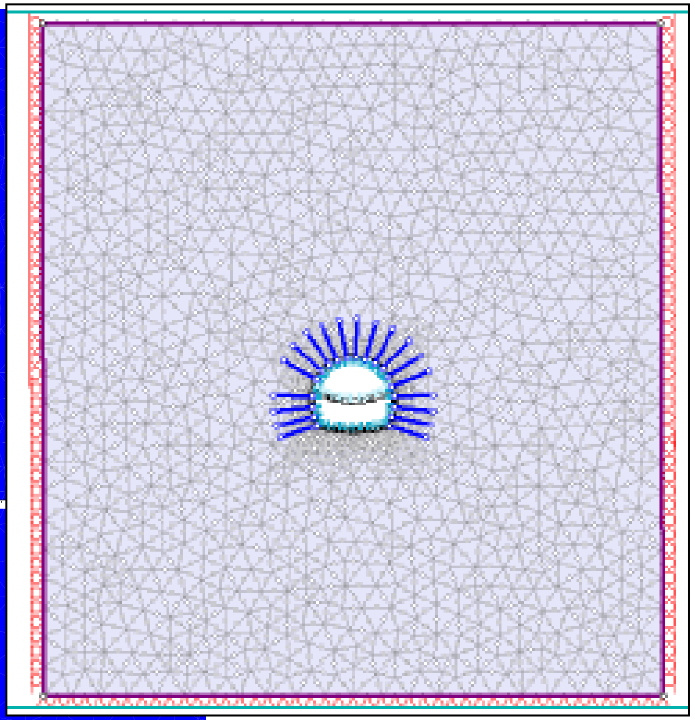
Figure 13: Major Principal Stress Contours for Rock Class I



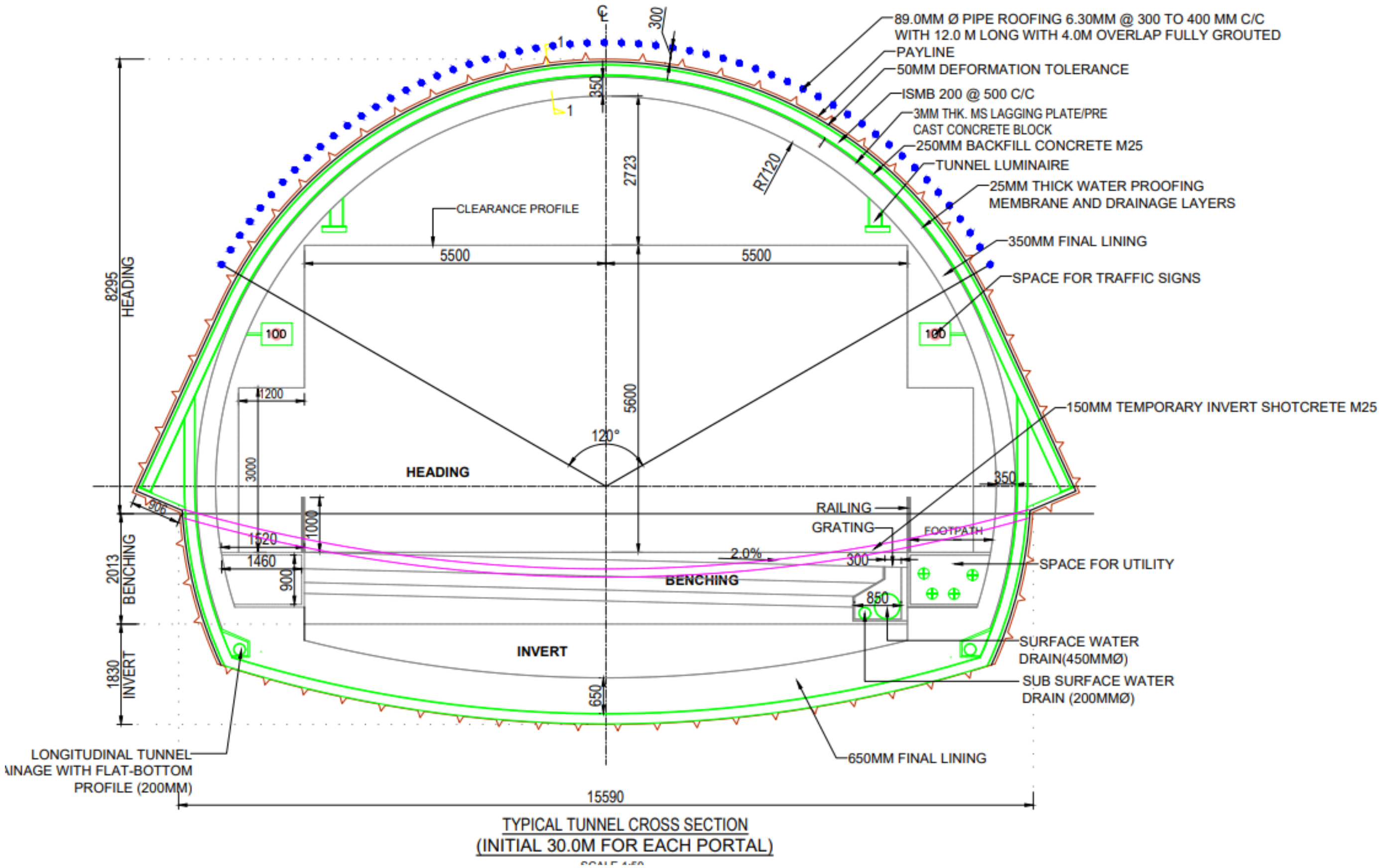
Numerical Models for Hard Ground and Soft Ground

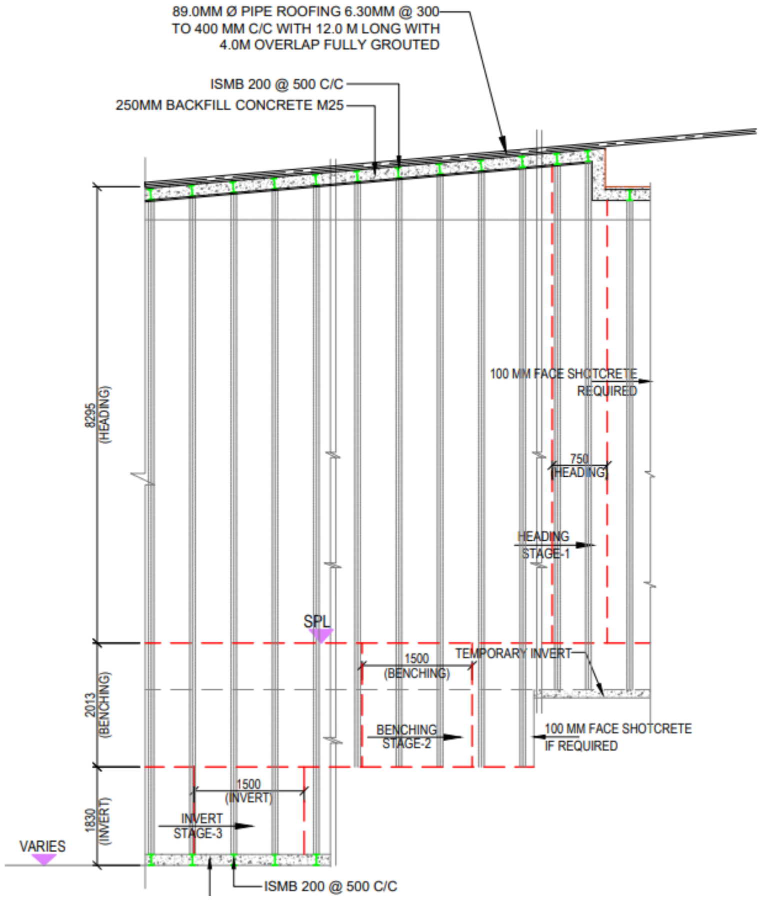




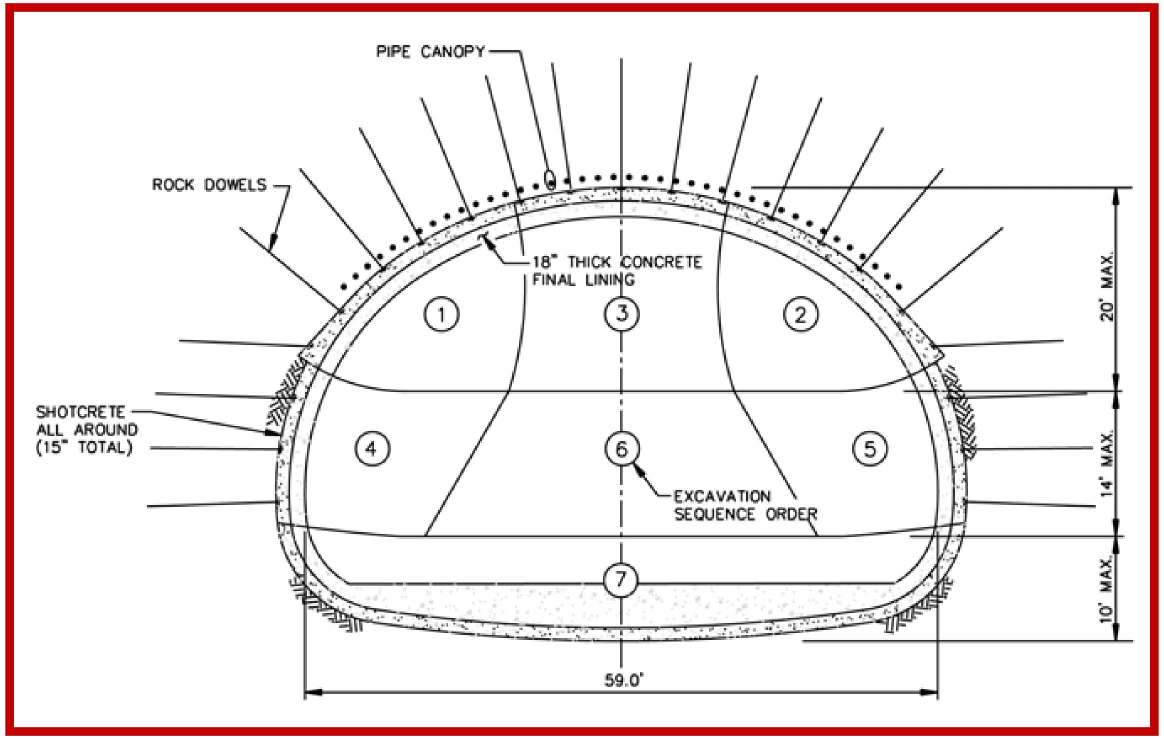


Typical Support System for Soft Ground





Typical Support System for Soft Ground



Typical Support System for Soft Ground

these estimates into a two-dimensional analysis. The current method used to choose the capacity and density of the face support is to make it roughly equivalent to the rockbolt pattern used in the tunnel walls. The length is generally the same as that of the forepoles.

In this example, the final concrete lining is un-reinforced and the analysis indicates that the stresses induced in the lining are well within allowable working loads, even under the condition of full external water pressure. In finalizing the lining design, it would also be necessary to check for any possible adverse effects from eccentric loading or thermal stresses.

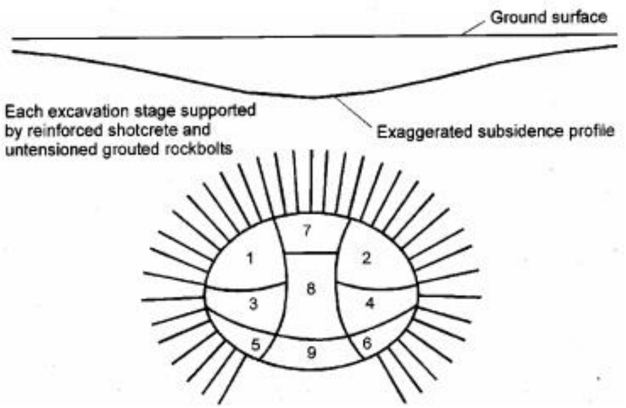


Fig. 18: Excavation and support stages for an underground station of the Athens Metro. Temporary support consists of double wire mesh reinforced 250 - 300 mm thick shotcrete shells with embedded lattice girders or steel sets.

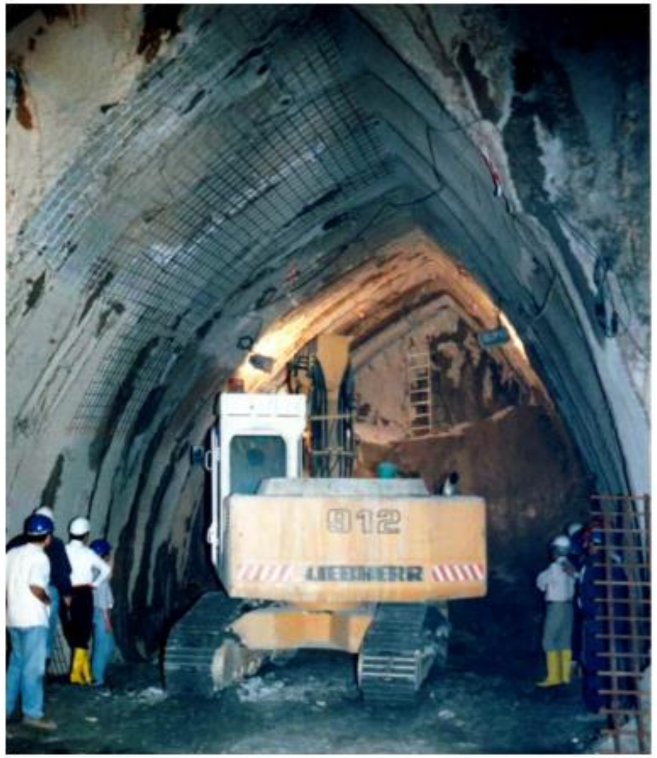


Fig. 20: Side drift in the Athens Metro Olympion station excavation.

Instrumentation and Monitoring in SEM/NATM

Essential component of NATM is Instrumentation and Monitoring

1. During & prior to tunnel excavation
   - Standpipe piezometers, extensometers are installed along tunnel alignment to account for sudden change in GW level and subsidence
2. During Excavation and Installation of Primary Support System

To check deformations, convergences and stresses in primary support system

- Optical Targets/ Bi reflex targets/Displacement targets
- Extensometers MPBX/Tape Extensometers, Measuring anchors
- Pressure cells, Stress meters, Load cells, inclinometers
- Piezometers

After final lining

- For long term stability monitoring of tunnel and structures on ground.

During construction, monitoring is done very frequently (fortnightly, weekly, daily). After construction monitoring frequency is reduced.

Tunnel Convergence

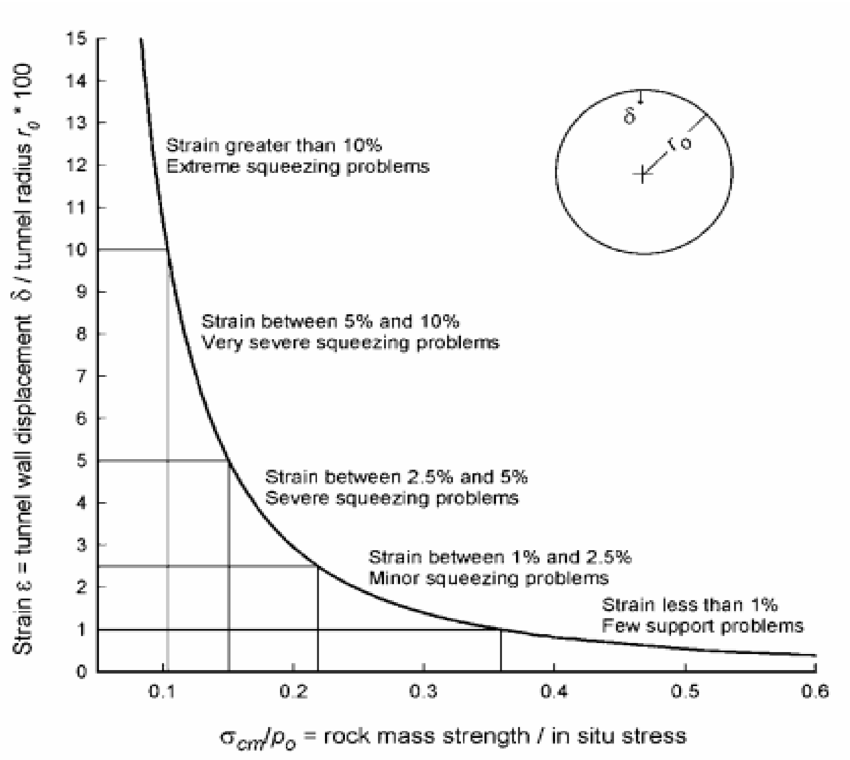
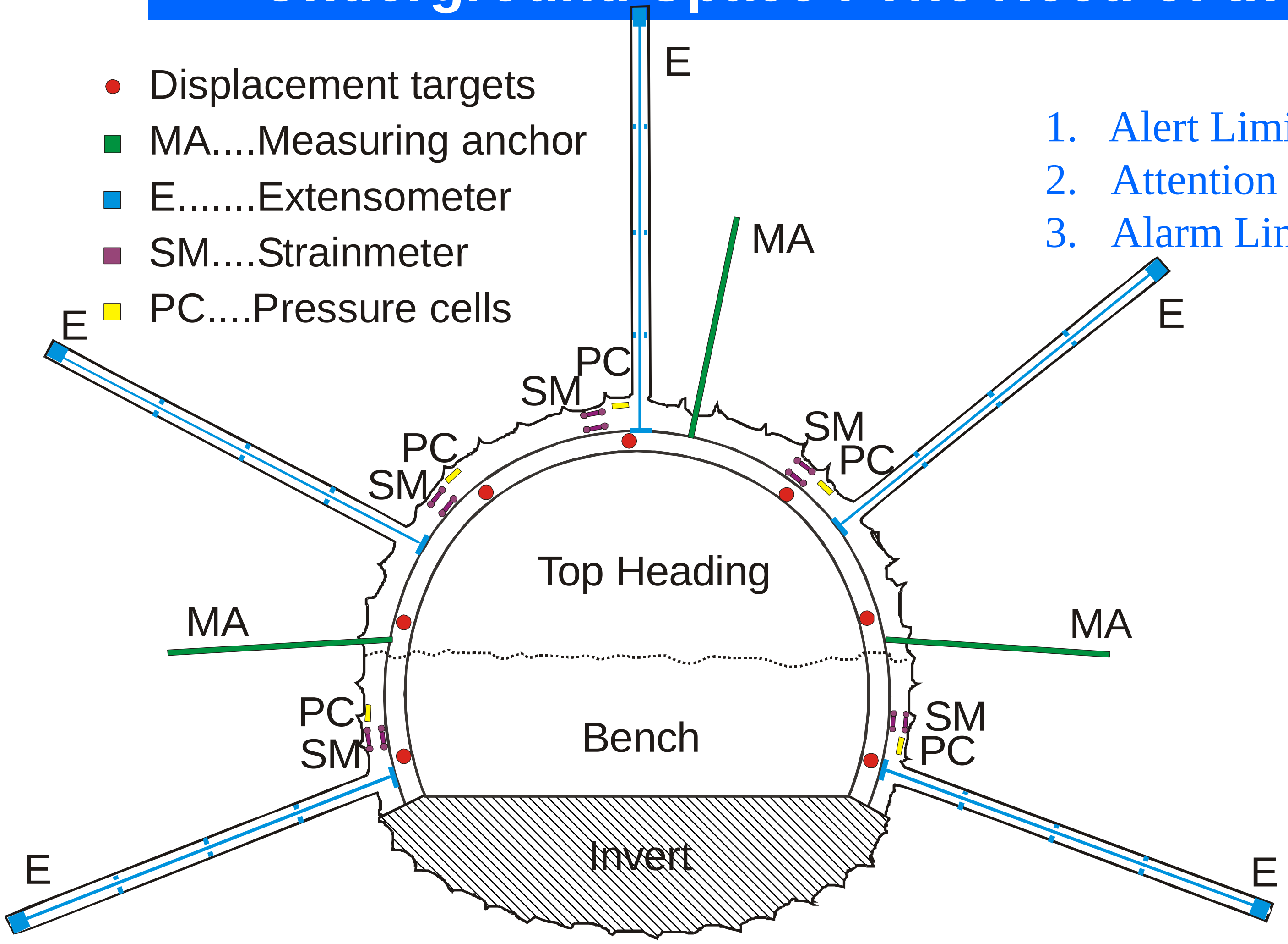
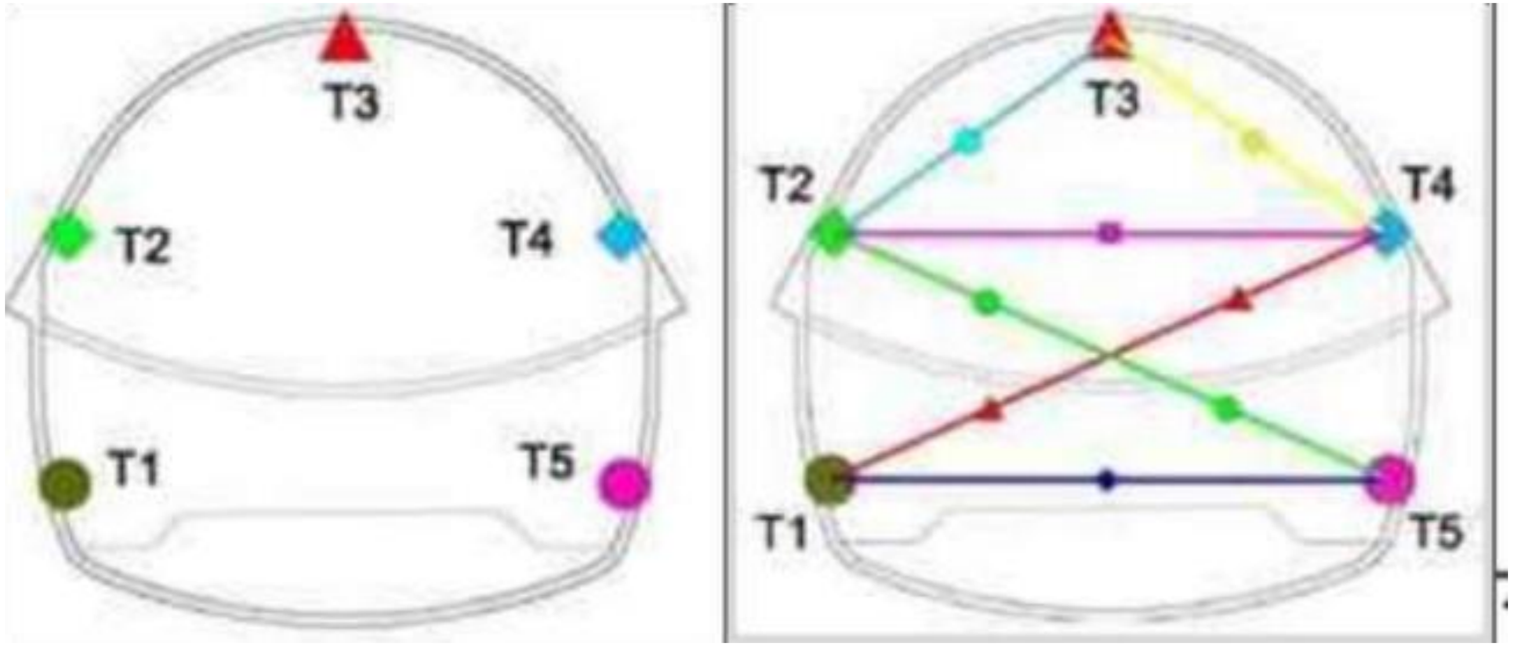


Fig. 12: Tunneling problems associated with different levels of strain.

Geotechnical Monitoring Section



1. Alert Limit: 50-60% of predicted deformation
2. Attention Limit: 70-80% of predicted deformation
3. Alarm Limit: 95 to 100% of predicted deformation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ASSOCIATION INTERNATIONALE DES TUNNELS ET DE L'ESPACE SOUTERRAIN
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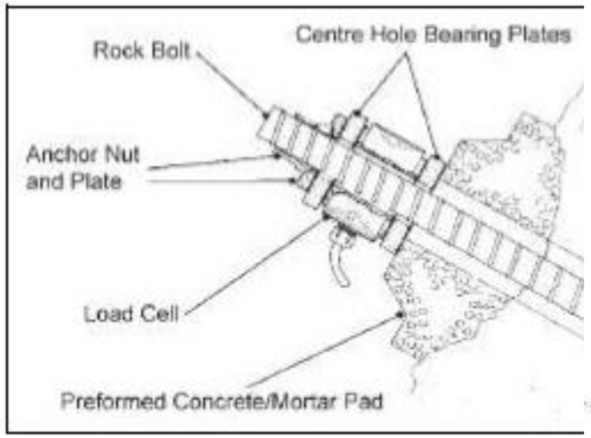
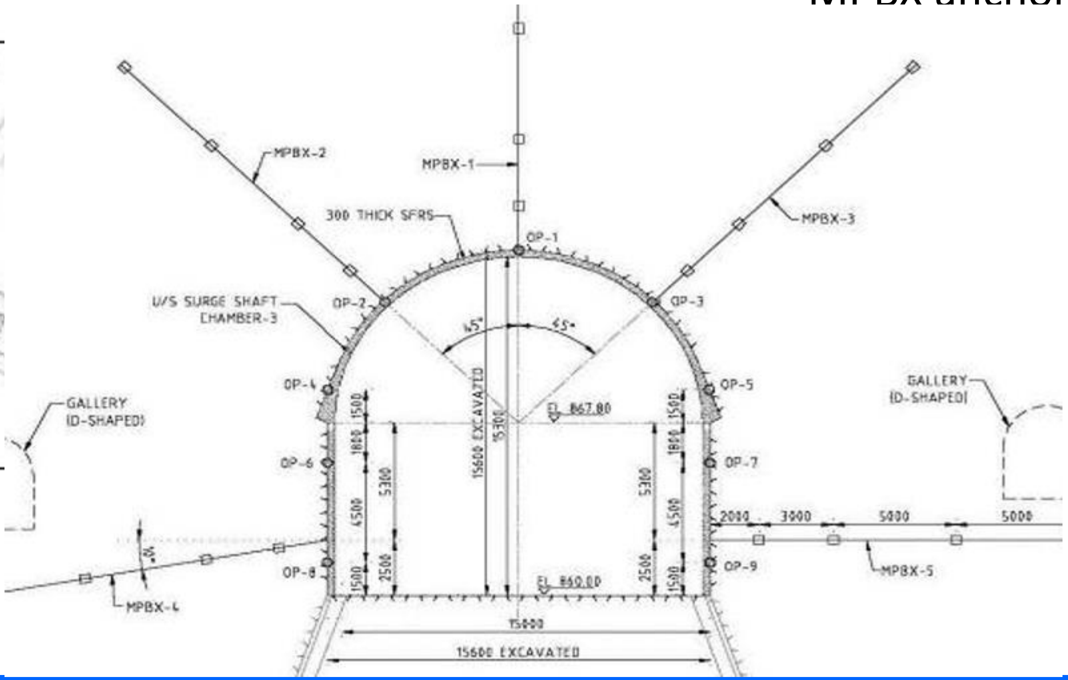
Bi-Reflex Target

MPBX anchor & rods



Load cell & its arrangement
With rock bolt



June 27th – 28th 2022, Mumbai, India

Some Examples

Some Examples

Some Examples

NATM by excavating machine

Free face excavating machine / partial face excavating machine
- They have a drilling boom with drum or disc mounted hard bits.
- By moving the boom according to designed shape, various section can be excavated.
- Lower noise and vibration than by blasting.
- Slower excavation speed than by blasting, in case of hard rock.
  - Usually applicable less than 100 ~ 200MPa (rock strength)

Road Header

Mobile Miner

Mobile Tunneling Machine

References:

[1] E. Hoek, "Support for very weak rock associated with faults and shear zones, International Symposium on Rock Support and Reinforcement Practice in Mining, Kalgoorlie, Australia," 14-19 March 1999, pp. 20.

[2] E. Hoek, and P. Marinos, "Predicting tunnel squeezing problems in weak heterogeneous rock masses," Tunnels and Tunnelling International, in press 2000.

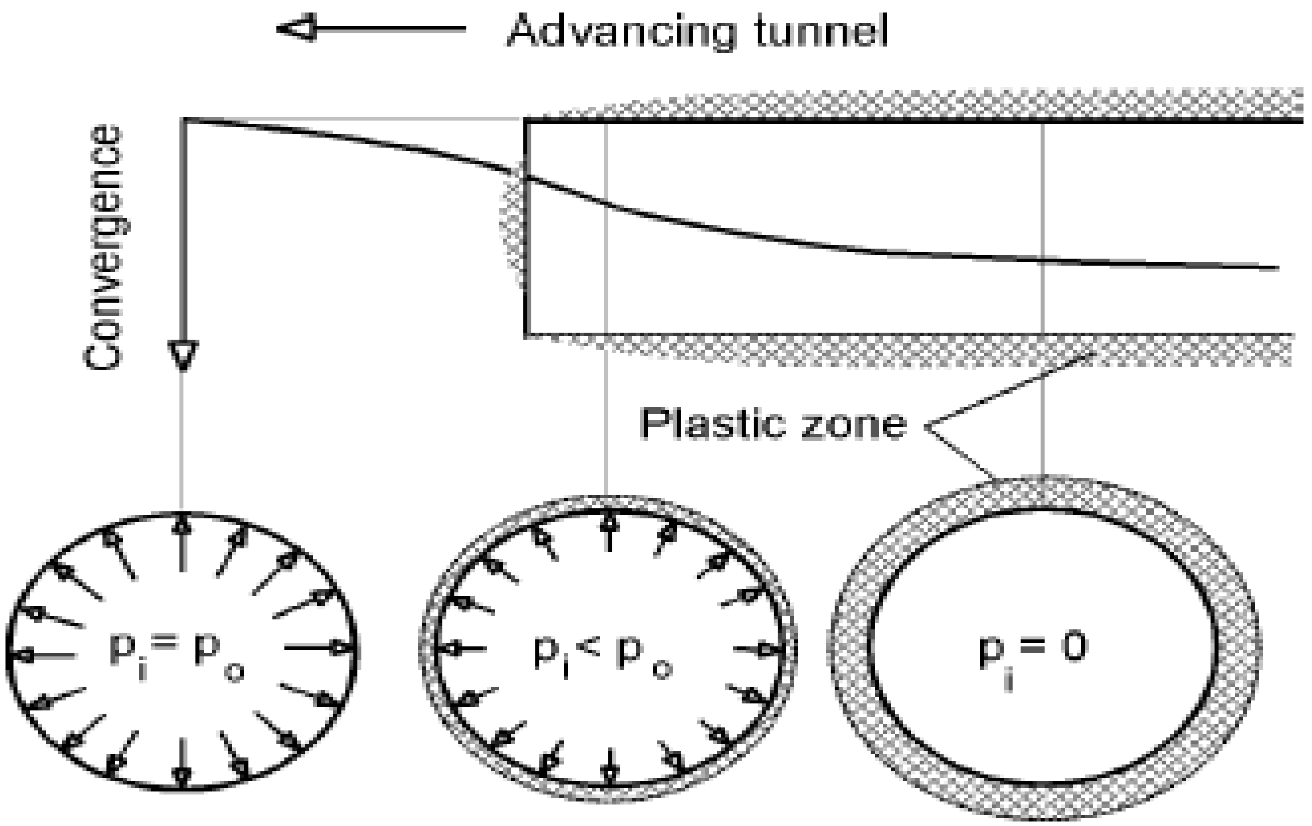
[3] E. Hoek, "Big tunnels in bad rock," ASCE Journal of Geotechnical and Geo environmental Engineering, Sept 2001, Vol. 127, No. 9, pp. 726-740.

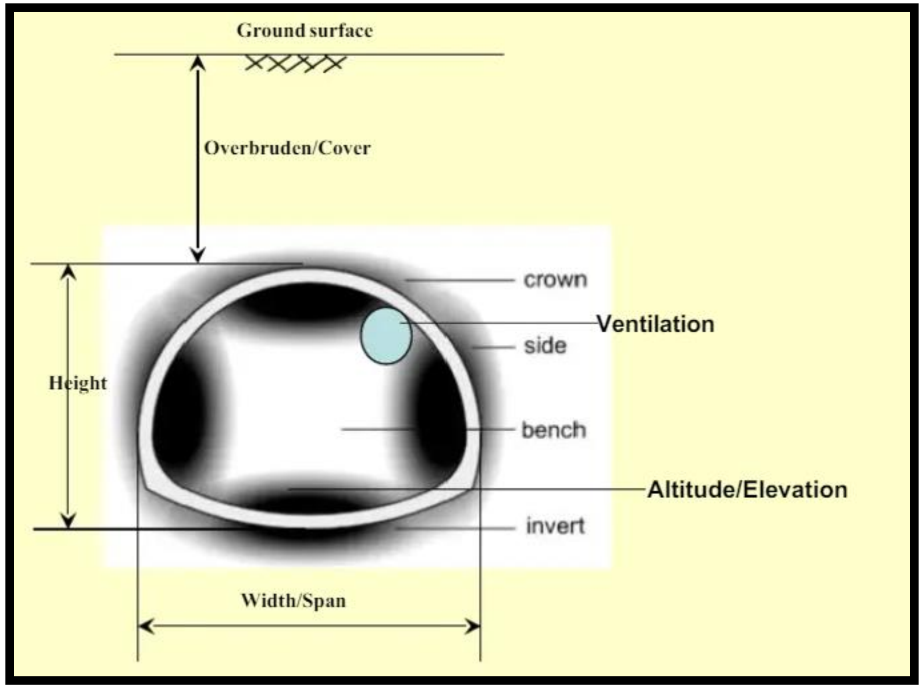
Thanks for Kind Attention

uvglobaldesign@gmail.com

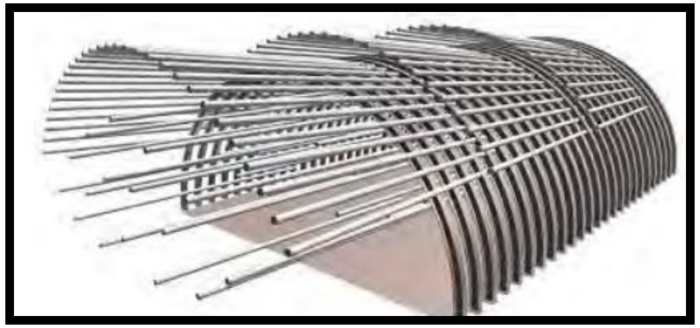
In between excavation of tunnel and installation of support a certain percentage of stress relaxation will take place. A percentage unloading method was used to approximate the three dimensional redistribution of stress around the two dimensional model.

In this analysis the ground relaxation allowed is 70% before installation of support. This value is assumed by combining the results obtained from ground reaction curve analysis and literature available on rock support interaction analysis. The variation of support pressure with some distance ahead of advancing face and some distance behind the advancing face is shown below.


Advancing tunnel
Convergence
Plastic zone
$p_i = p_o$
$p_i < p_o$
$p_i = 0$



Ground surface
Overbruden/Cover
crown
Ventilation
side
Height
bench
Altitude/Elevation
invert
Width/Span



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ホイールジャンボ
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International Conference on

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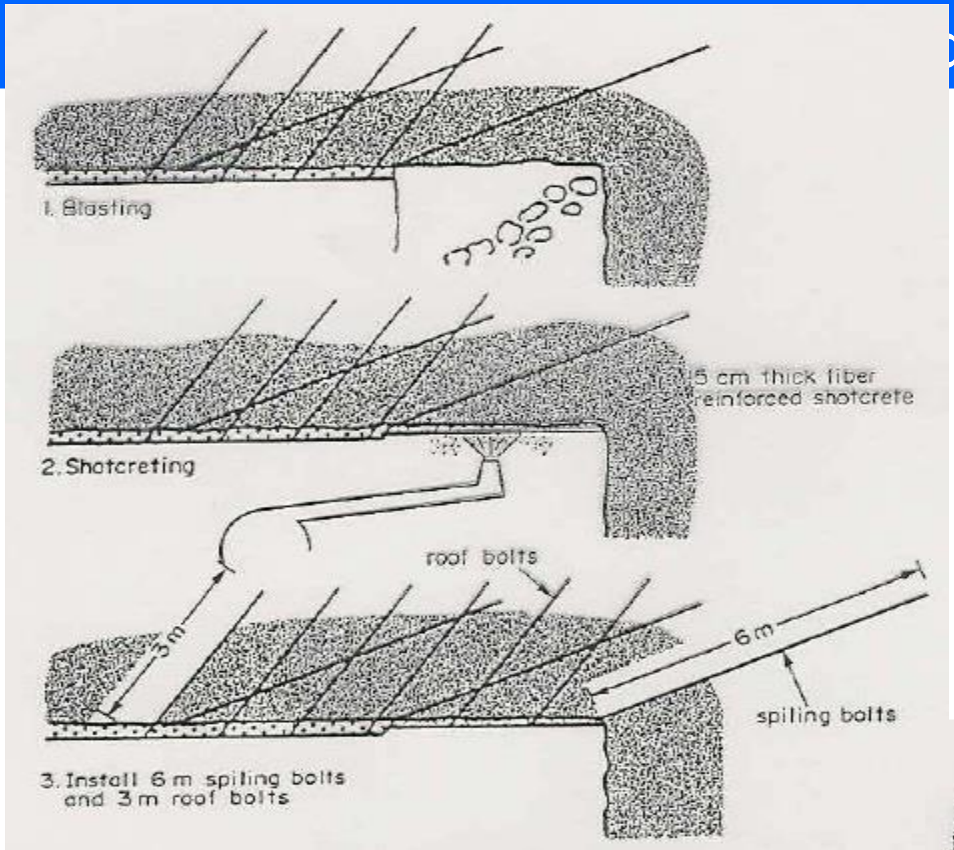
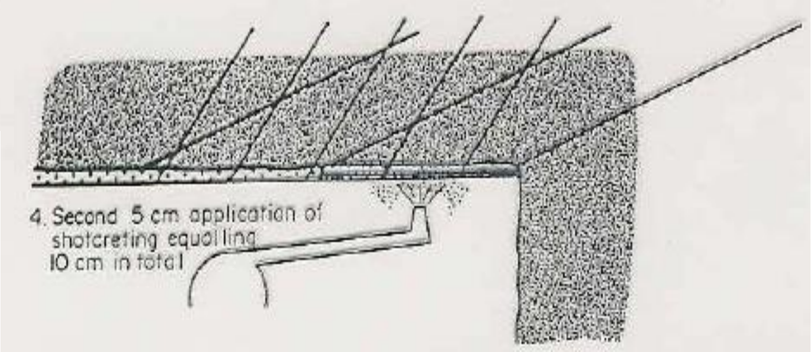
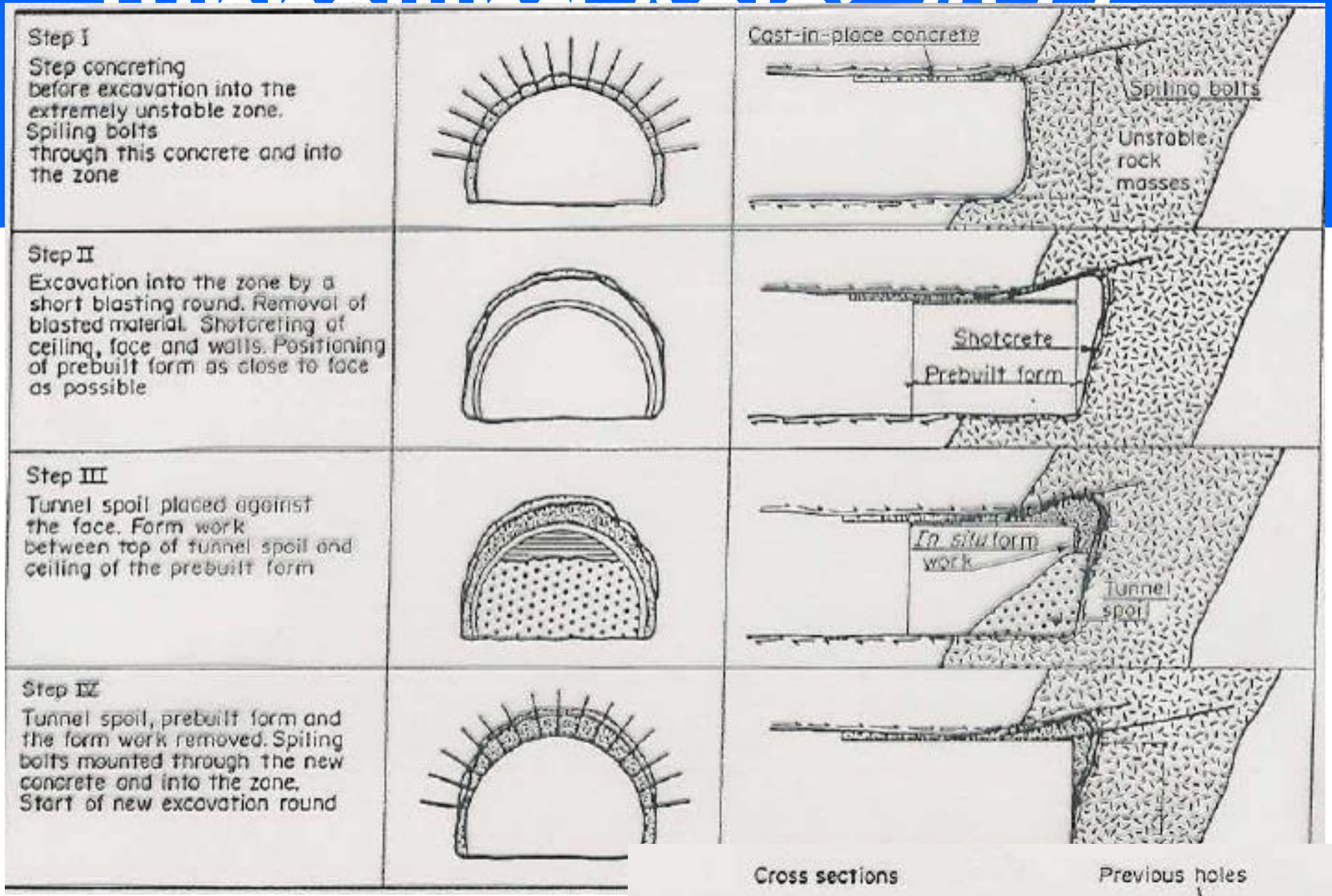
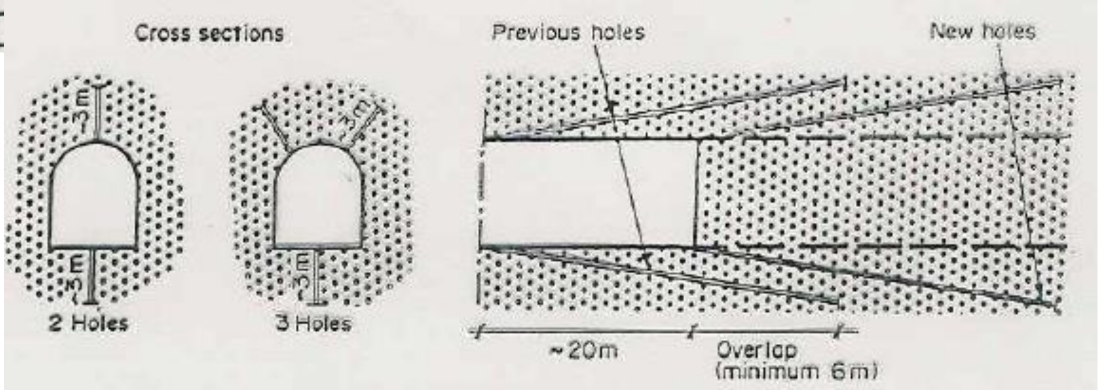
Use of Spiling bolts for heading excavation



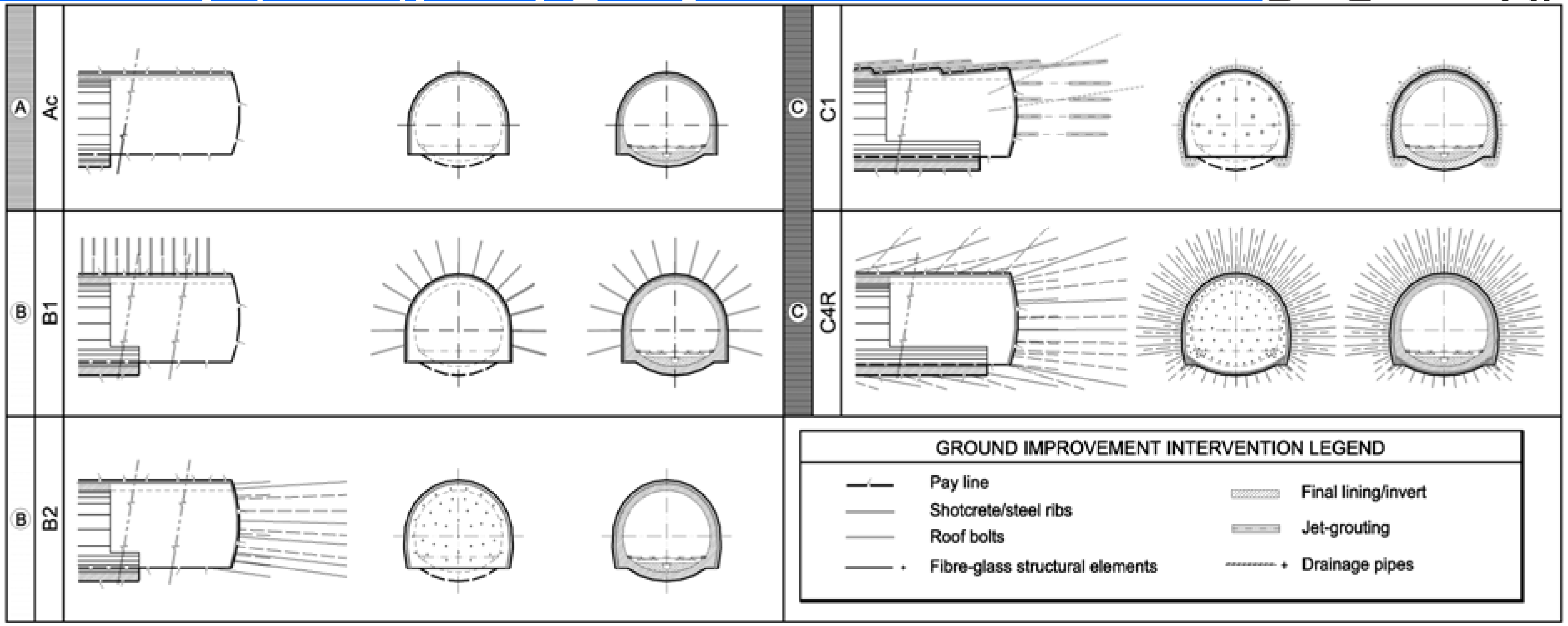






Excavation steps for unstable heading

(ii). Face instability



Underground alignment is divided into sections based on the predicted stability of core face in absence of stabilization measures :

– Stable core face (Behavior category A): Deformation in elastic range. Instability manifested are falling ground at face & around cavity
– Core face stable in short term (Behavior category B): Deformation in Elastic-plastic range. Instability manifested are spalling at face & around cavity
– Core face unstable (Behavior category C): Deformation phenomena in failure range. Instability manifested are failure of face and collapse of cavity