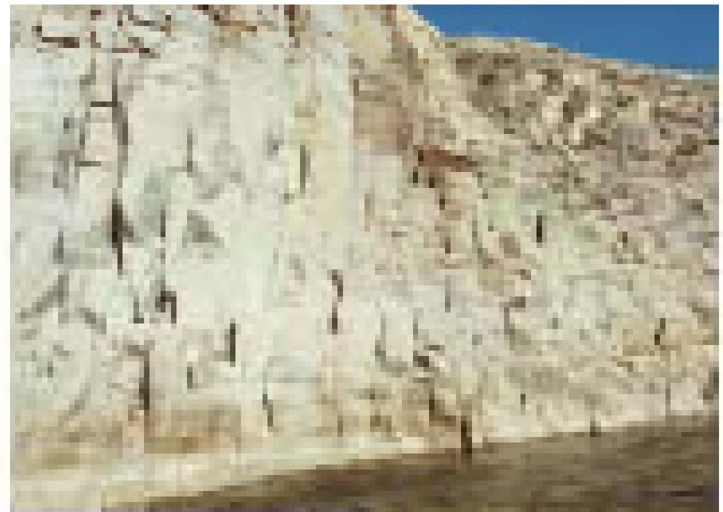
Rock masses



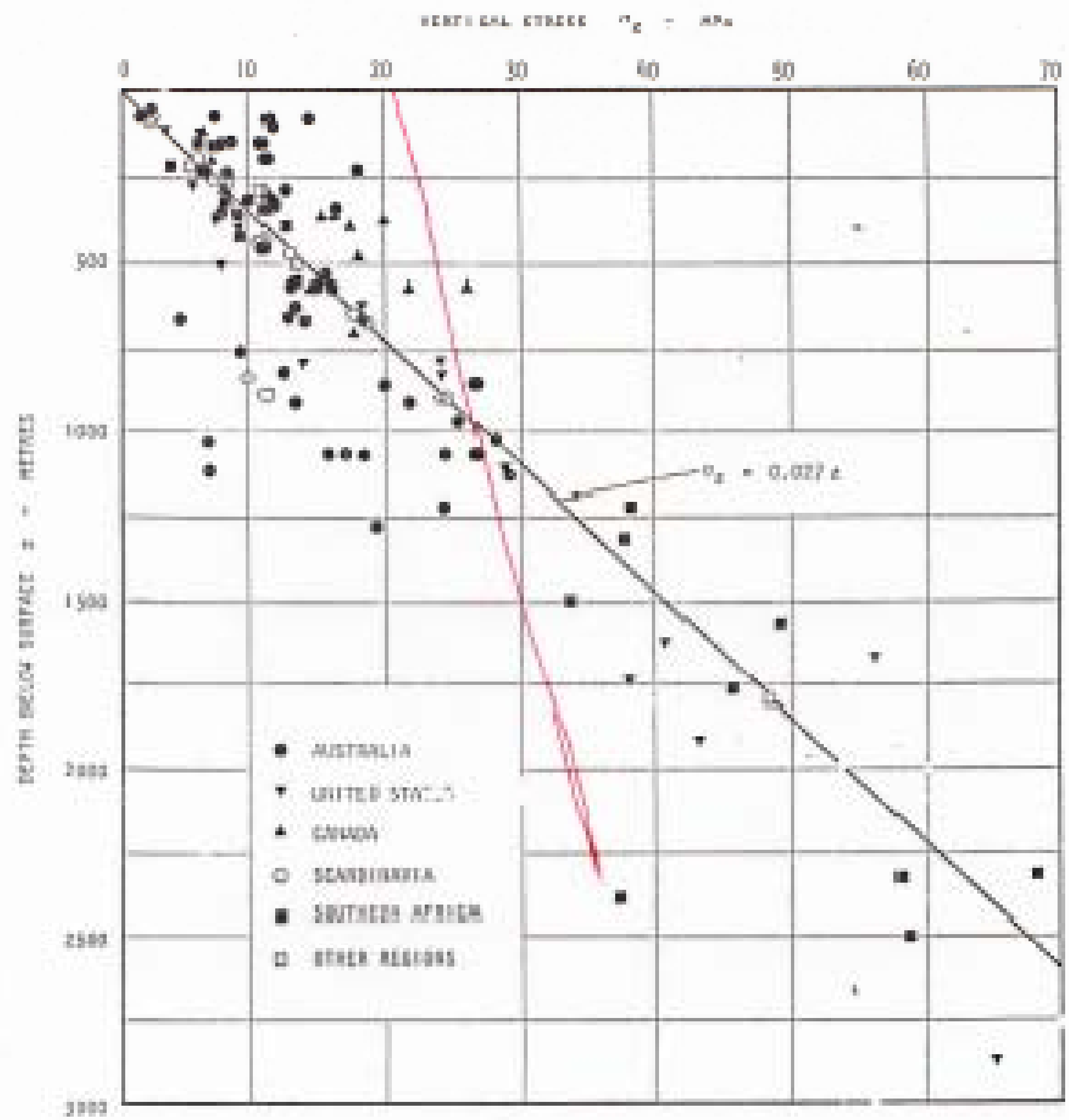


Figure 40 : Plot of vertical stresses against depth below surface.

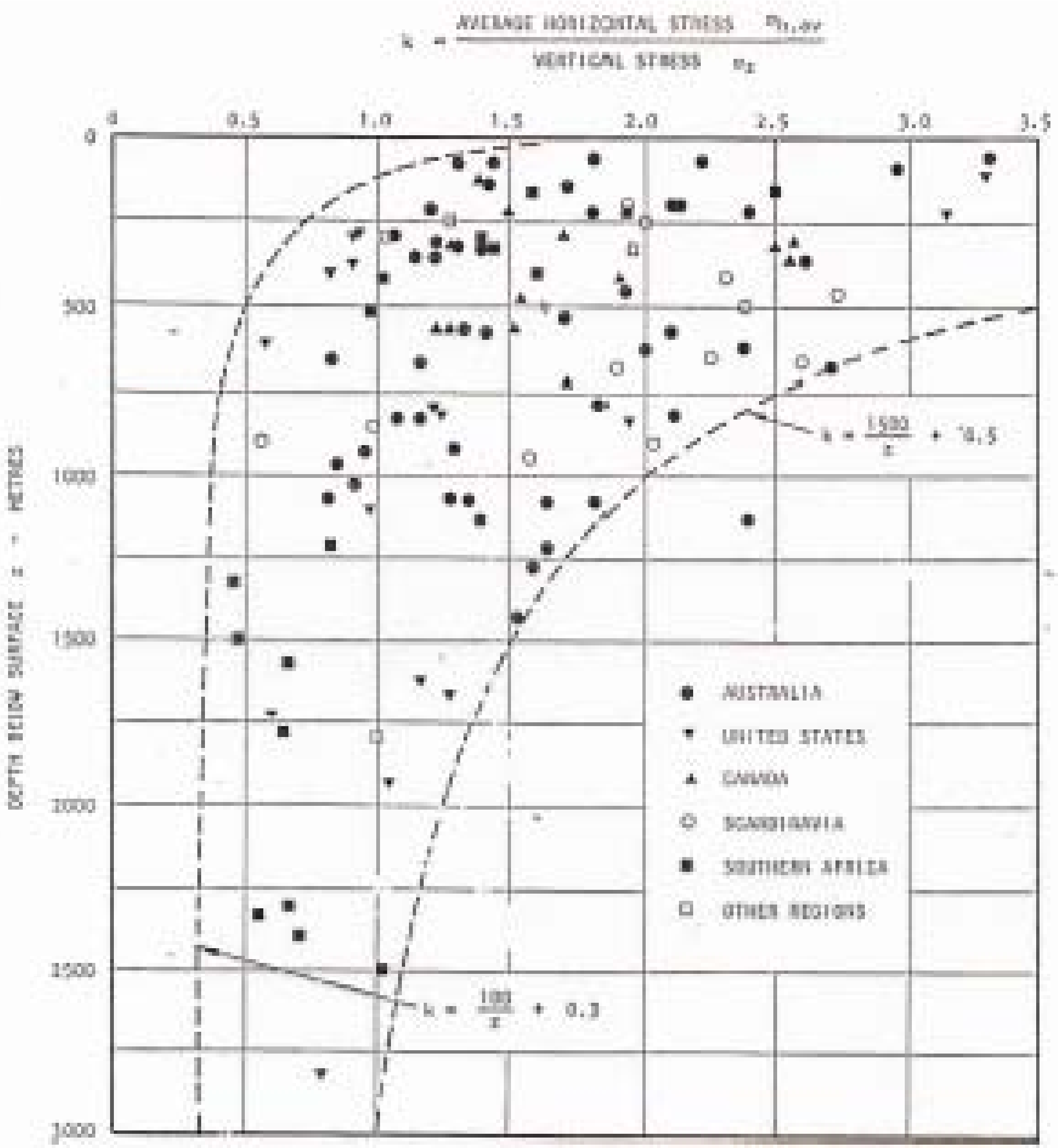


Figure 41 : Variation of ratio of average horizontal stress to vertical stress with depth below surface.

Basic Definitions

- Swelling Pressure – Due to volumetric Expansion of a rock mass having swelling minerals when comes in contact with water
- Primitive stress – Stress in the state of equilibrium
- Induced stress - Due to creation of opening
- Immediate or short term rock pressure - Pressure which develop within a short span of 1 -4 weeks of time.
- Ultimate Rock Pressure – Pressure developed Ultimately
- Ground Reaction Curve – A relationship between support pressures and radial displacements of the tunnel wall. The rock pressure depends on tunnel wall displacement and it is not a unique property in squeezing ground.

- Squeezing Rock or Ground Condition: Rock mass fails when the tangential stress exceeds its uniaxial compressive strength. Overstressed due to high cover pressure or high tectonic stress.
- Coefficient of Volumetric Expansion: It is defined as the ratio between increase in volume of the rock mass after failure and its initial volume.
- Degree of Squeezing: The ratio of UCS of rock mass to the tangential stress is adopted to define the degree of squeezing

  $= q_c / 2p$.

  Rock Pillars: When several closely spaced tunnels are constructed, a pillar of unexcavated rock mass is left unexcavated between two adjacent tunnels to provide the support called as Rock Pillar.

- Squeezing pressure: Result of such plastic deformation which will reveal themselves as pressures only when deformations are arrested.
- Broken Zone: Bounded by the locus of the points around a tunnel opening where the induced tangential stress exceeds the insitu strength of rock mass. Also known as ‘Coffin Cover’.
- Compacting Zone: A fragile rock mass around a tunnel opening

What is site characterization?

- Engineering geological investigation of the rock, rock discontinuities and rock mass at site and in laboratory
- Integral part of the engineering design process for any projects involving the ground
- Important for layout planning, support design and costing
- Also an important tool for construction safety

- Rock material and rock mass properties
- Discontinuities and their conditions (joints, faults, shear zones)
- Ground water and water pressure
- In-situ stress

Techniques for site investigations

- Geological mapping (exposure and discontinuities)
- Geophysical surveys (detective work)
- Exploratory drilling (soil drilling and diamond core drilling)
- In-situ testing (rock mass properties)
- Laboratory testing (rock material properties)

Geophysical surveys

- Seismic refraction and reflection
- Electrical resistivity
- Coupled seismic reflection (good vertical resolution) and electrical resistivity (good horizontal resolution) strong recommended
- Obtains data on overburden thickness, bedrock elevation, seismic velocities of geological layers, and major geological structures

Type	Methods	Objective
Drilling	Soil boring; diamond core drilling	Overburden, and rock cores
Surface geophysical surveys	Seismic refraction/reflection; electric resistivity tomography	Main geological structures; overburden depth
Borehole surveys and testing	Borehole logging; seismic logging; borehole camera acoustic imaging; impression packer; borehole radar; Lugeon tests; rising head/falling head tests; cross-hole tomography	Ground temperature; Seismic velocities; joints; and permeability; geological structures
Laboratory tests	Point load; uniaxial/triaxial compression; Brazil tensile; 3-point flexural	Mechanical properties of intact rock and rock joints
In situ stress	Hydraulic fracturing; 3-D overcoring	Hydraulic fracturing; 3-D overcoring (during construction)

Geology, Geology, Geology

- Explore before you draw..pick the best host rock mass..
  - Modicum of data/rational analyses needed at start - simple is OK
  - RMC's guidance only ~ questionable application in high stress?
  - Modeling is a powerful, but good input is critical..garbage in..
- Likely Stability Issues
  - Stress-Driven Yield and/or Burst (overstress)
  - Gravity-Driven Fall-Out (blocks, wedges, soil-like fill)
  - Water pressure and inflow (erosion, shear strength reduction)
  - Combinations of the above
- Early Site Investigation Objectives (reduce uncertainties):
  - Rock - Intact rock strengths
  - Stress - In Situ Stress levels/orientations
  - Fracture - Discontinuities
  - Water - head, permeability, estimates flow locations and rates)

Rock Mass Assumptions..

- Basis of Conceptual Design ~ data + assumptions
  - Representative Behaviors (routine variability)
  - Local Adversities ~ frequency/severity
  - Pre-SI Baseline Documentation of both <u>Knowns & Unknowns</u> -> no more sophisticated than the data can support!!
  - More assumptions = more contingency
  - Rule #1 - avoidance preferred to mitigation
- Pending SI - assume a hard & blocky rock mass
  - Relatively strong and abrasive intact rocks 100MPa+
  - Containing fractures and fracture zones, some with water
  - Subject to significant stress at depth

Stability of Underground Openings

Underground, two forms of instability often observed:

1) Geo-structurally-controlled, gravity-driven processes leading to block/wedge fall-out
2) Stress driven failure or yield, leading to rockburst or convergence

(after Martin et al. IJRM&MS, 2003)

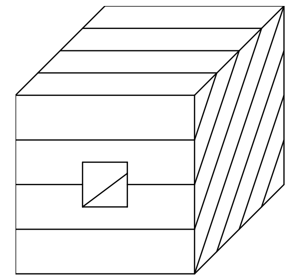
Note: structure and stress can act in combination to produce failure and adding water can exacerbate failure or reduce the FOS against failure through the action of flow and/or pressure

Orientation of Major Excavations

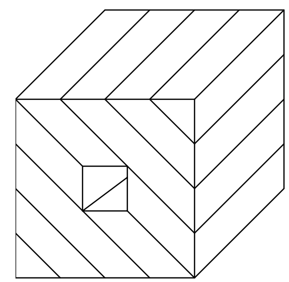
- Consider Orientation with respect to Stress Field and Geo-Structure (discontinuity-bound blocks/wedges)
  - 1) If there is a major fault or fracture zone in the volume of a major excavation find a new site! (e.g data before design!)
  - 2) If a single dominant discontinuity set is present
    - Minimize gravity-driven fall-out by placing the long axis of the excavation sub-perpendicular to the strike of the discontinuity set.
  - 3) If multiple sets are present avoid placing the long axis parallel to any - give more weight to sets most likely to cause instability.
  - 4) If high stresses are unavoidable at a site
    - Destabilizing forces..gravity always..rock stress/water pressure sometimes
    - A little stress and fracture can aid stability
    - Minimize yield, slabbing, rockburst activity avoid placing the long axis of the perpendicular to the principal stress (~15-30 degrees from parallel, after Broch, E. 1979).

Rock Fracture - Orientation

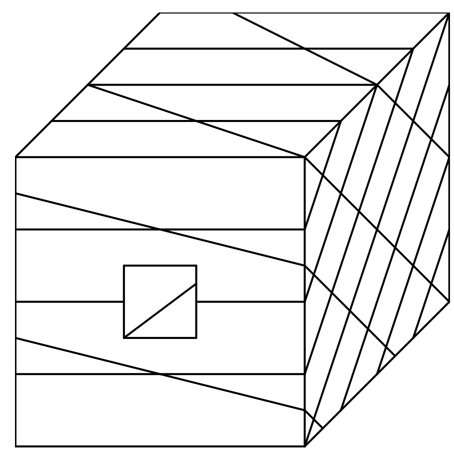
- Single Set of planes of weakness. Stability is a function of Excavation Axis:
  - Maximize - Strike Perpendicular
  - Minimize - Strike Parallel
- More typically multiple sets of planes of weaknesses..
  - Maximize by avoiding having any strike close to parallel to axis.



Excavation Axis Perpendicular to Discontinuity Strike

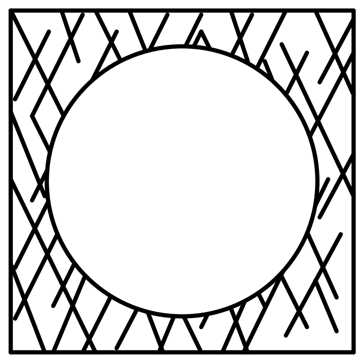
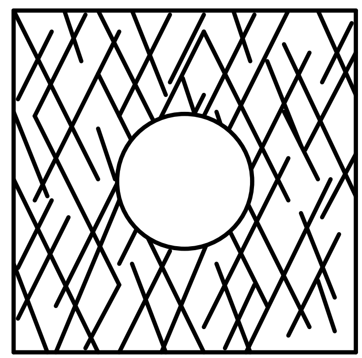
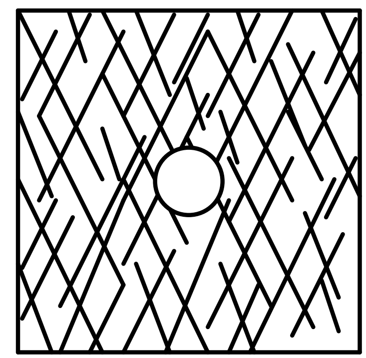
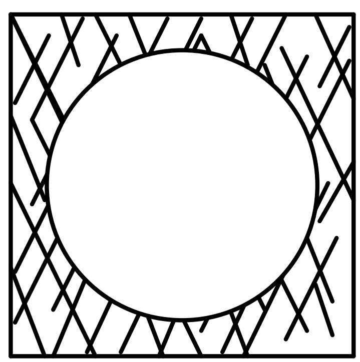
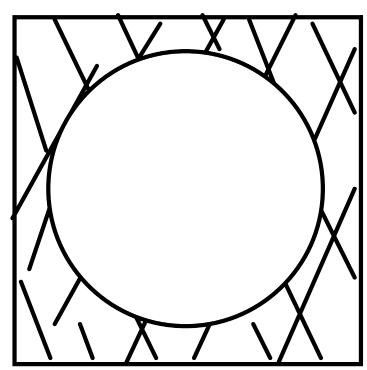
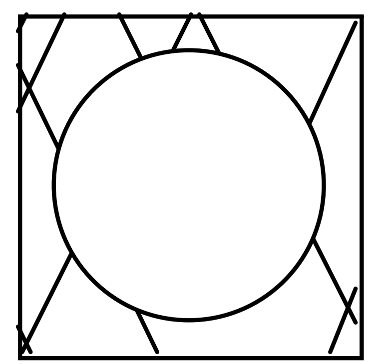


Excavation Parallel to Discontinuity Strike



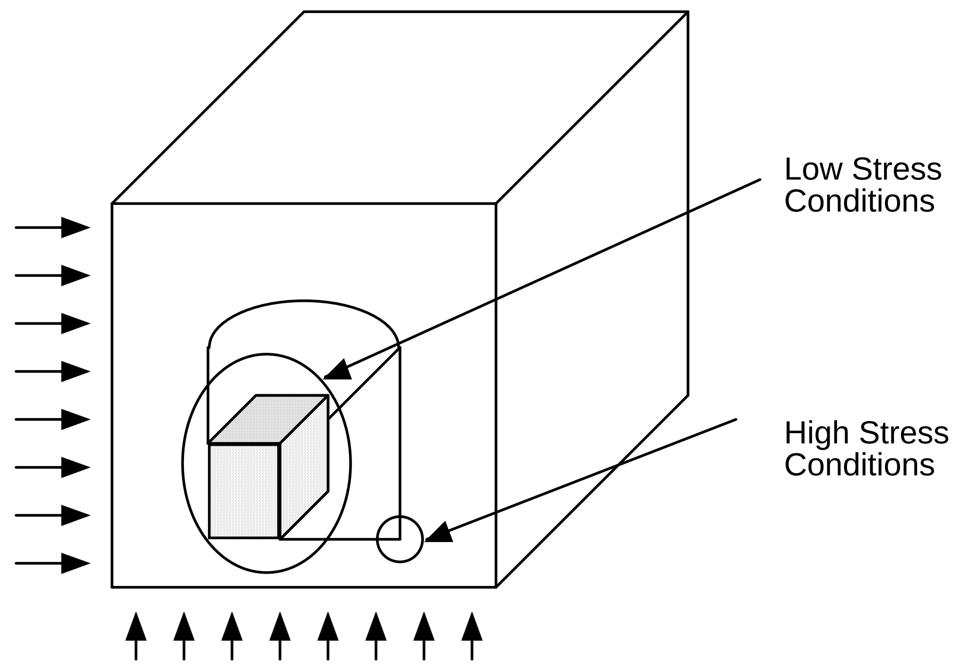
Rock Fracture - Size/Scale Effects

Larger Excavation -> increased potential for blocky fall-out

Bored Diameter	8 meters	4 meters	2 meters
Rock Mass Structure on an Absolute Scale 8 meters			
Rock Mass Structure on the "Tunnel Scale" Tunnel Diameter			

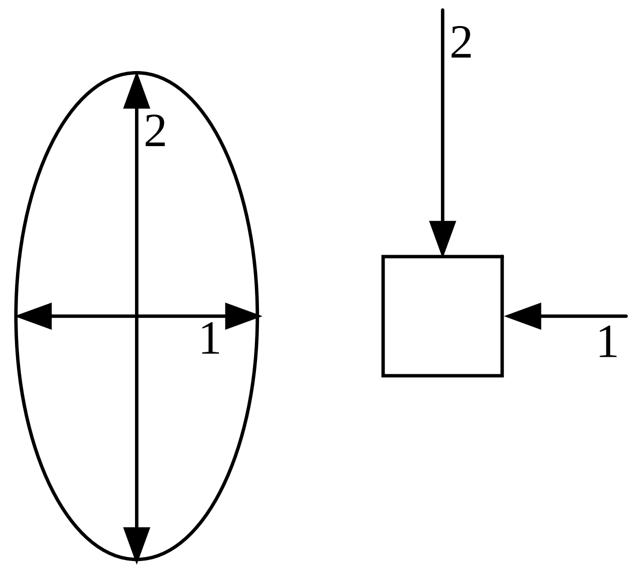
High & Low Stress

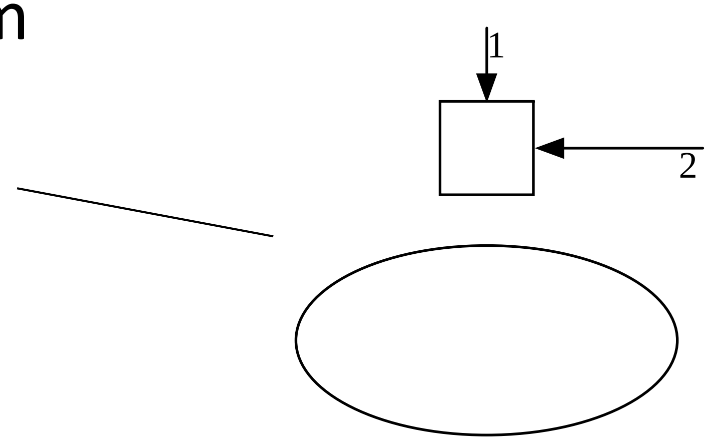
- Excavation results in stress redistribution at perimeter:
  - Low Stress or Tension: mobilized shear strength will be low - Failure!
  - High Stress: locally, tangential stresses may exceed rock strength - Failure!
- Above conditions can result in fall-out (walls, crown)
  - Geometry of fall-out material a key consideration
  - Ideally eliminate or limit the zones of both high and low stress around the perimeter



Mitigating Stress -Section Shape

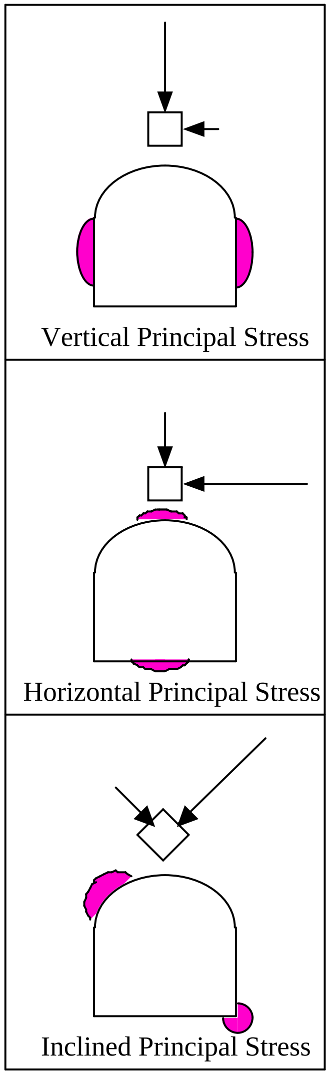
- Minimum Boundary stresses occur when the axis ratios of elliptical or ovaloid openings are matched to the in situ stress ratio after Hoek+Brown
- Nice to keep the bottom flat. However, some designers go the whole hog (counter arch..), Sauer..





High-Stress Failure Zones

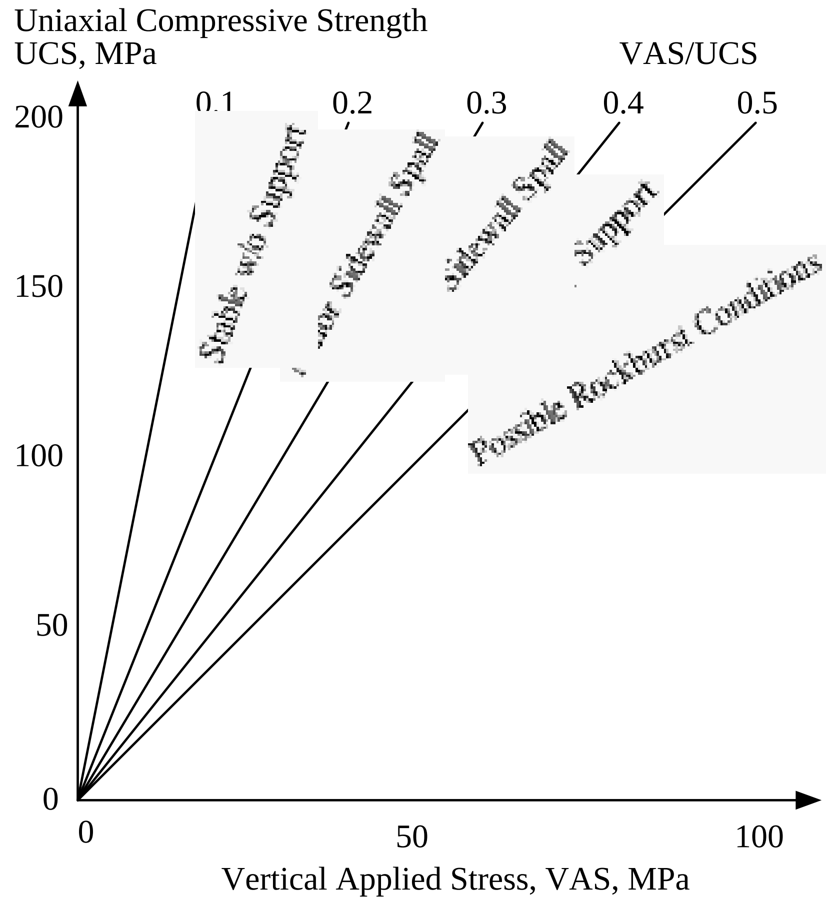
- Not always practical to have circular/elliptical sections..
- Stress concentration will occur as a function of stress field/orientation and excavation shape
- Shaded areas show where rockburst or yield is most likely to occur around a horseshoe opening under three types of principal stress orientation..
  – Vertical
  – Horizontal
  – Inclined



After Selmer-Olsen+Broch

Stress-Driven Instability can be Severe

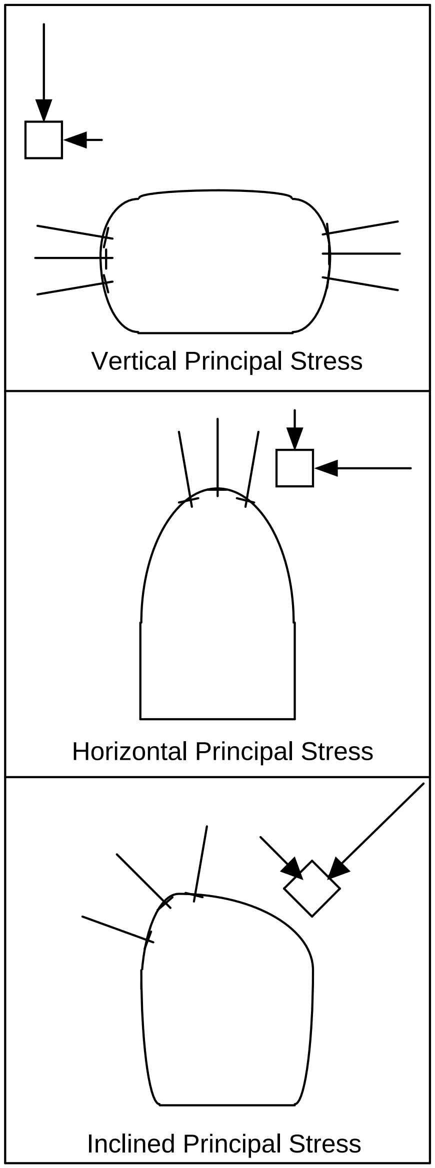
- Severity Prediction?
  - relative to Virgin Stress vs. Intact Strength Ratio
- Overstress Failures
  - Under moderate stress regime aim to even-out the distribution of stresses to avoid local stability problems, as discussed
  - Under higher stress localize stress concentrations to reduce unstable area and costs of support…



After Hoek+Brown

Section & Support Mitigation

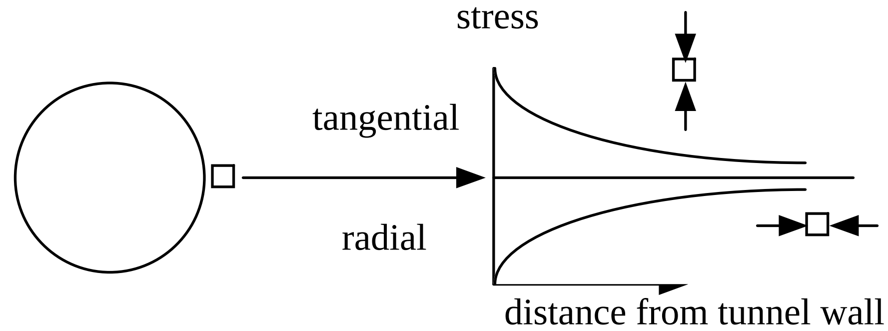
- Strategy for Minimizing Impact of Overstress
  - Vertical Principal Stress
    - Reduce potential for buckling/slabbing by avoiding long perimeters sub-parallel to principal stress - “low” excavations
  - Horizontal and Inclined Principal Stresses
    - Focus and support highly stressed volume at discrete locations around the section by increasing radii of curvature of section to concentrate loading
  - bolt support can be used to stabilize areas of concentrated loading

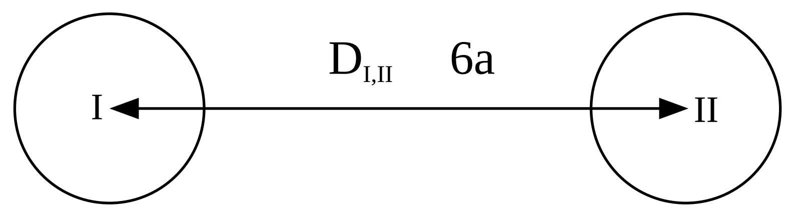


after Selmer-Olsen+Broch

Mitigation Step: Opening Separation

- Virgin stress conditions are modified when openings are made, at the perimeter (hydrostatic stress)
  - Radial stress zero
  - Tangential stress 2x virgin
- 2 circular openings
  - Shared diameter, a
  - In hydrostatic stress field
  - Minimal Interaction if distance between openings centers is greater than 6a
- In high stress situations, ensure openings do not overly encroach on zones of influence





After Brady & Brown

Introduction: Rock Tunnelling

Rock tunnelling involves:

Rock excavation – to make a hole.

Rock support – to sustain the hole.

Rock Excavation:

Excavation technology is primarily driven by rock excavation machine technology.

Rock Support:

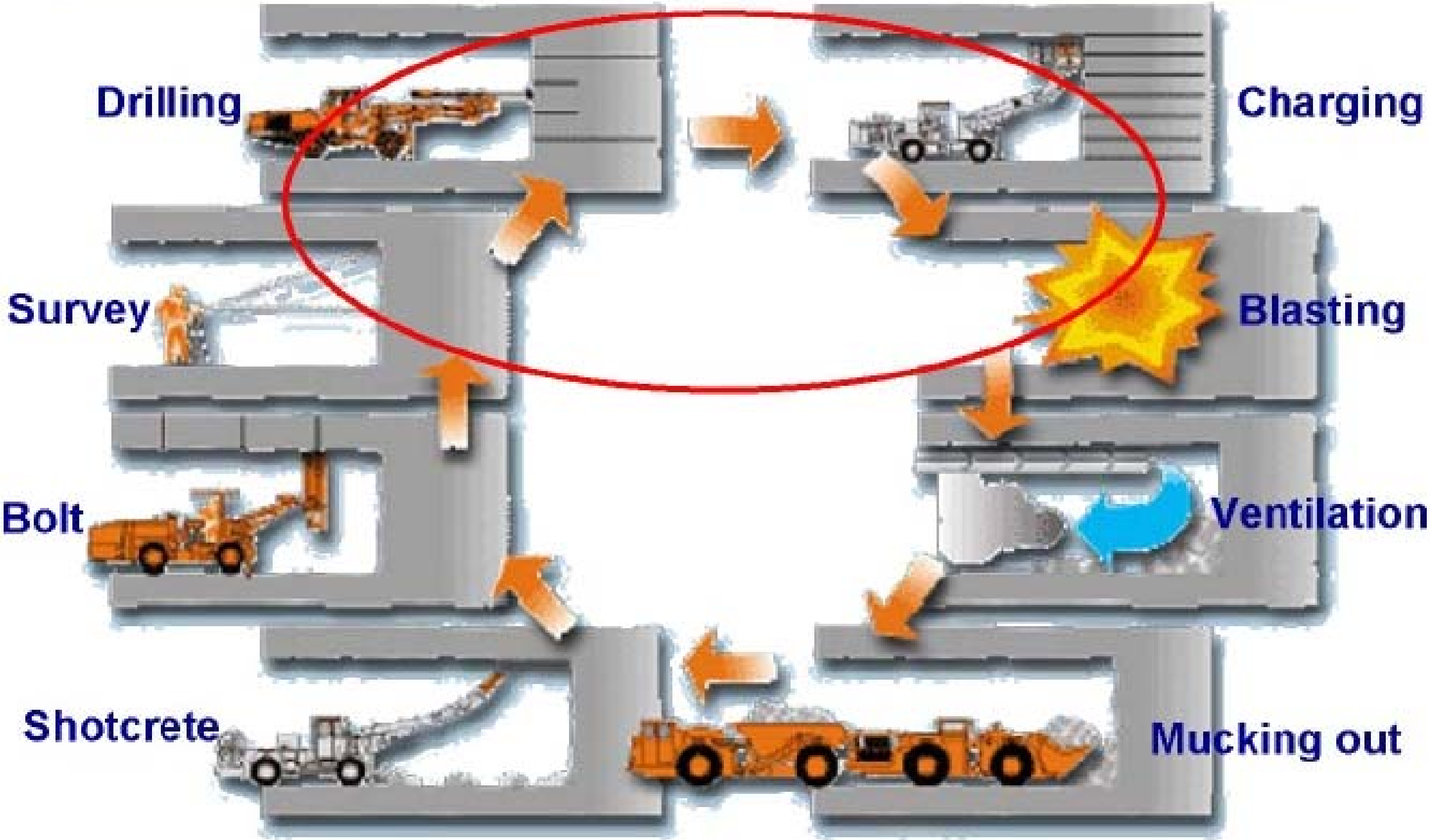
Support technology is largely driven by rock mechanics science together with support material technology.

Tunnel Excavation

Modern rock tunnels are excavated by primarily two methods:

- Drill-and-Blast (D&B): It involves drilling charge holes advancing into rocks and using explosives to blast the rocks.
- Tunnel Boring Machine (TBM): It involves cutting rock by a full face boring machines. Tunnelling machines for partial face (roadheader) are also used for rock excavation.

Rock Excavation: Drill-and-Blast



Rock Excavation: Drilling Technology

In 1850s, compressed air drilling was invented for rock drilling.

Since 1945, tungsten carbide drilling bits have been used.

In 1960s, pneumatic drilling was introduced.

In 1970s, hydraulic drilling was introduced and remains the main drilling method today.

Since 1980s, computer aided rock drilling started.

Rock Excavation: Blasting Technology

Before 1860s, black powder was used.

In 1860s, dynamite was invented and used in hard rock tunnelling.

1922, Electric initiation (1 second delay) introduced.
1940s, short delay detonators (10-100 ms) used.

1955, ANFO (ammonium nitrate fuel oil) introduced.

In 1960s, water gel and slurries.

In 1970s, non-electric initiation developed.

In 1980s, emulsion explosive developed and used in tunnelling since 1990s.

Rock Excavation: Blasting Technology

Emulsion explosives are water resistant, safe and pumpable, and produce less toxic gases.

Charging blast holes with emulsion explosives to excavate the Singapore Underground Ammunition Facility (UAF) storage caverns.

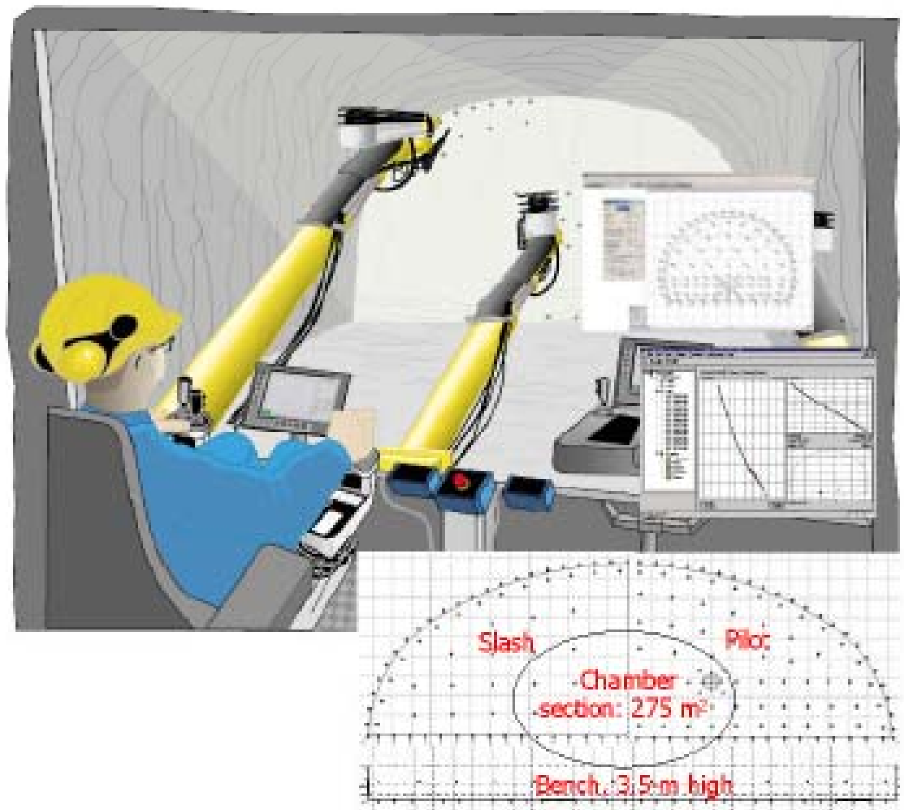
Rock Excavation: D&B Today

Computerized and automated hydraulic drilling jumbos are widely used. Drilling plans are stored in computer, precise positioning and navigation are by laser. Excavated profiles can be scanned for guiding next drilling and blasting.

In Lötschberg base tunnel (section about 70 m^2), over 6 m/day average progress for 4.6 km in granite, gneiss, schist and limestone, with maximum 16 m/day in granite.

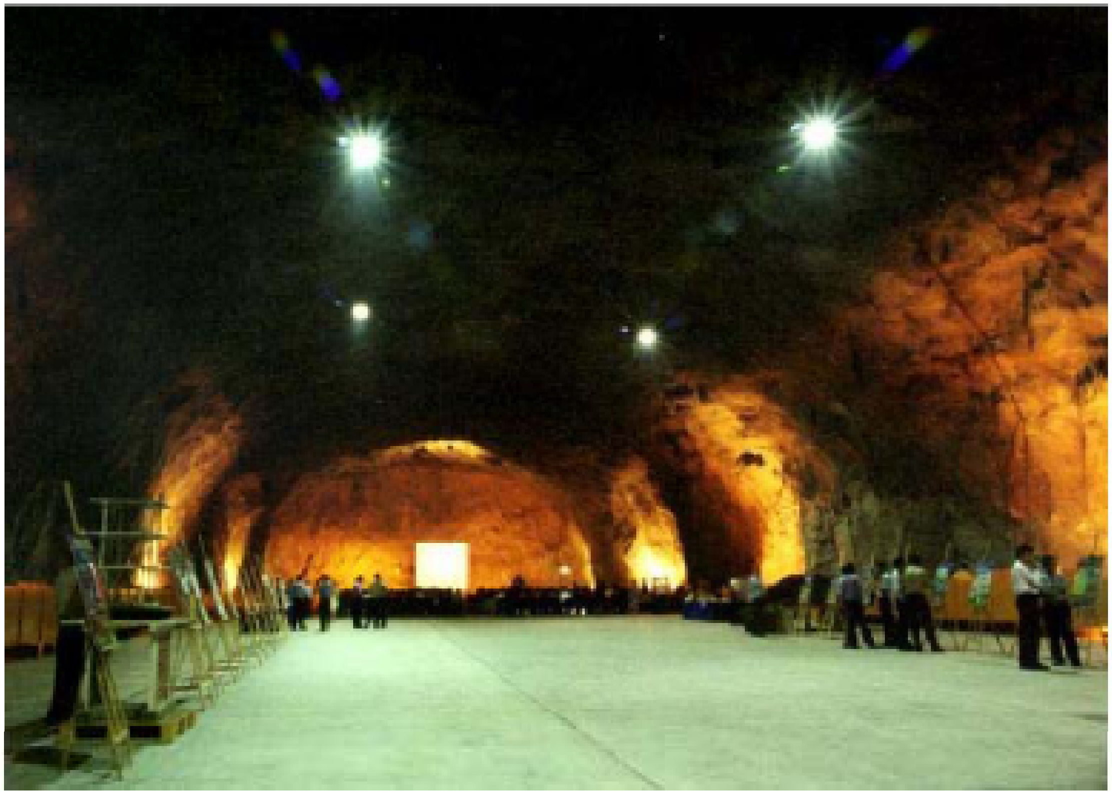
Rock Excavation: D&B Today

Computerised 3-boom drilling jumbos used in Singapore UAF caverns



Computerized and automated hydraulic drilling jumbo, with drill plan stored in computer. No marks on the face.

Emulsion explosives combined with non-electric initiation system are used to provide a safer and more efficient tunnelling operation. Quantity of pumpable emulsion can be controlled by computerized system.



Emulsion explosives were use to blast this and other granite caverns in Singapore (1999-2002). Emulsion explosive were stored on site.

Rock Excavation: TBM

Tunnel Boring Machine (TBM) is an excavation machine cutting the rock full face by pushing and rotating the cutterhead. Tunnel support is done behind.

Rock Excavation: TBM Technology

1851, invented by Wilson, first attempted at the Hoosac tunnel.

In 1950s, TBMs made by Robbins successfully excavated the Oahe Dam (shale) and Humber Sewer (hard rock) tunnels.

In 1990s, >50% tunnel volume in Switzerland are by TBMs.

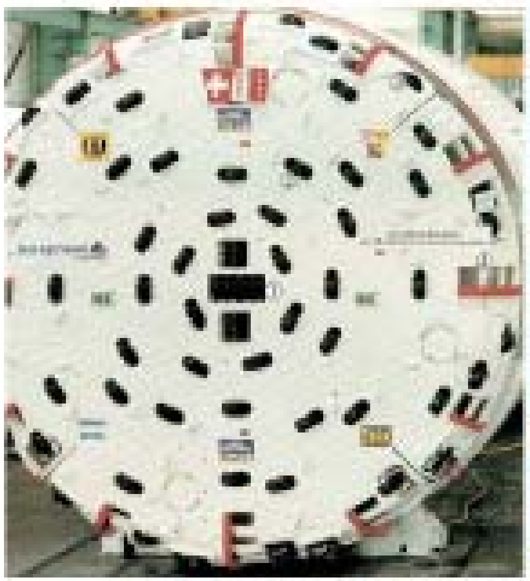
Channel tunnel (1994), 52 km (39 km undersea), by TBMs.

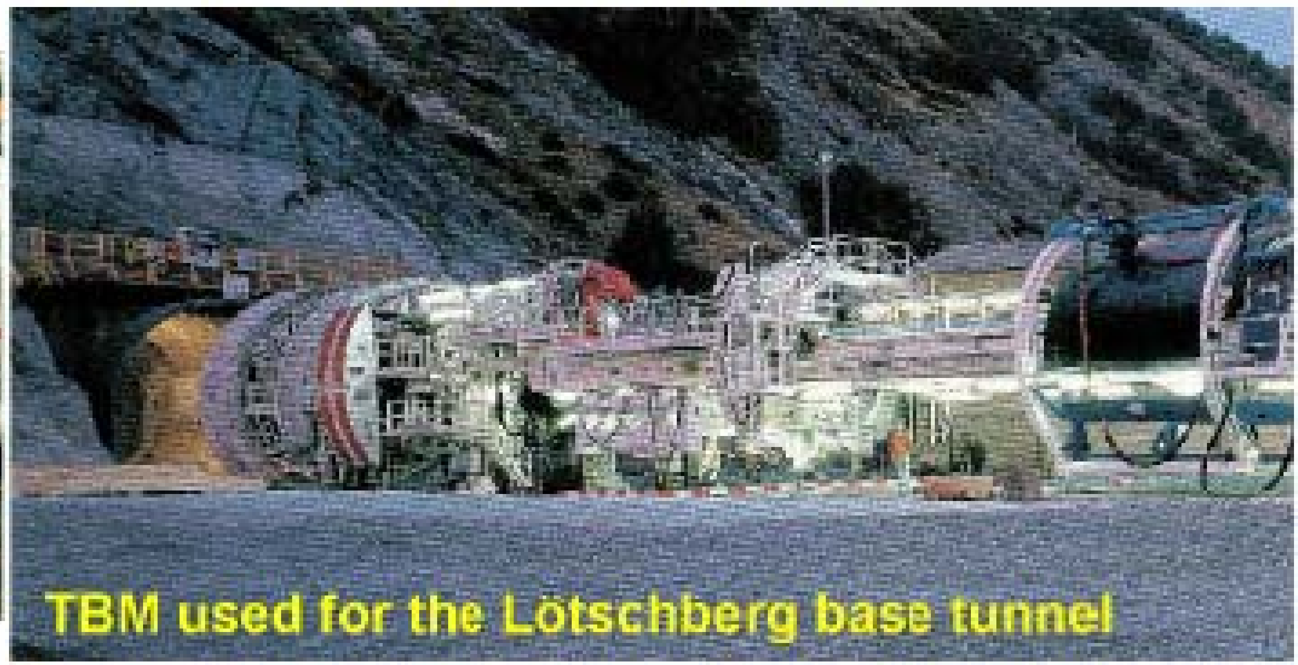
In 1960s, roadheader was introduced to tunnelling.

Rock Excavation: TBM Technology

Gotthard base tunnel, longest tunnel (57 km), with maximum overburden of 2.4 km to be completed soon, about 90% by TBM.

Niagara tunnel, with largest TBM, ø14.4 m.

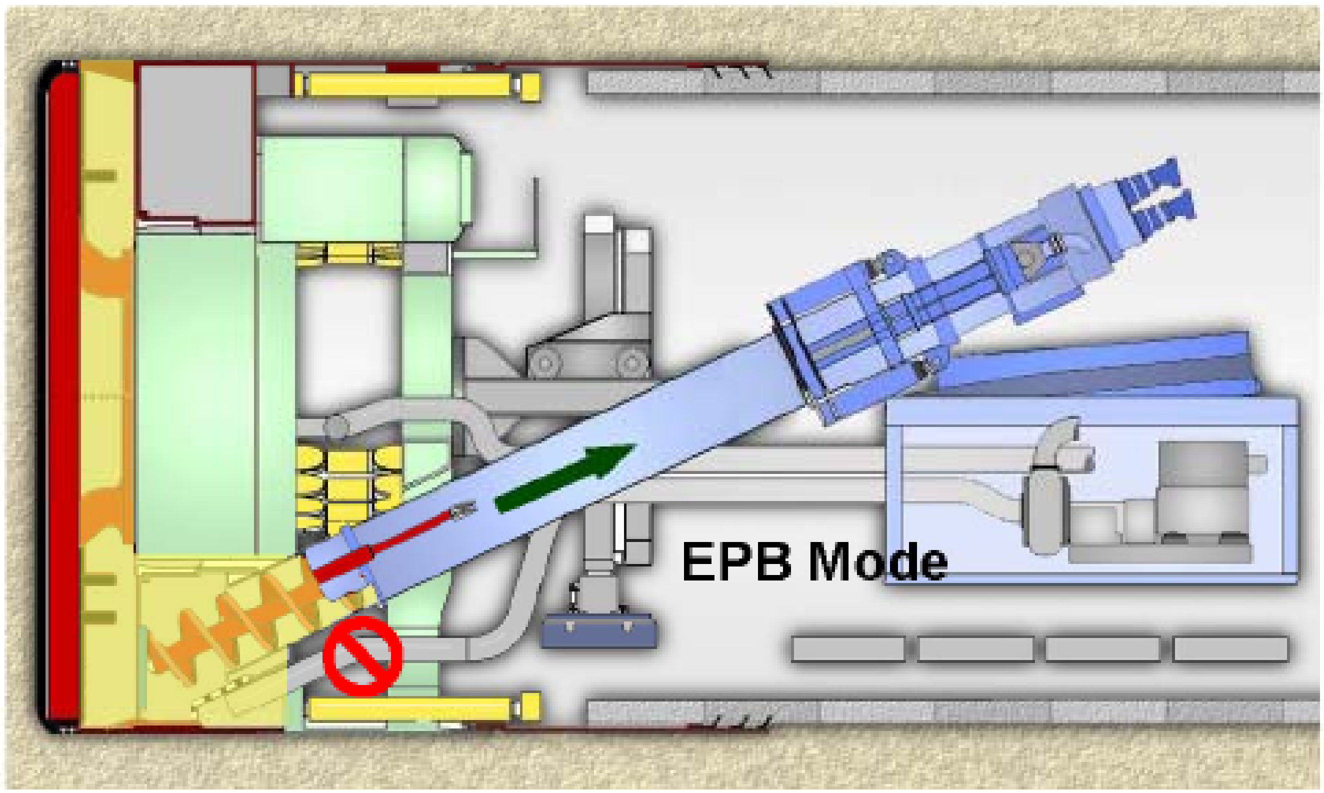




Rock Excavation: TBM Today

Wide choice of TBMs for rock tunnelling, with diameter >14m, gripper, single shield, double shield, EPB, slurry and mix-shield, for different ground conditions.

Convertible EPB–slurry TBM for poor rock and mixed ground



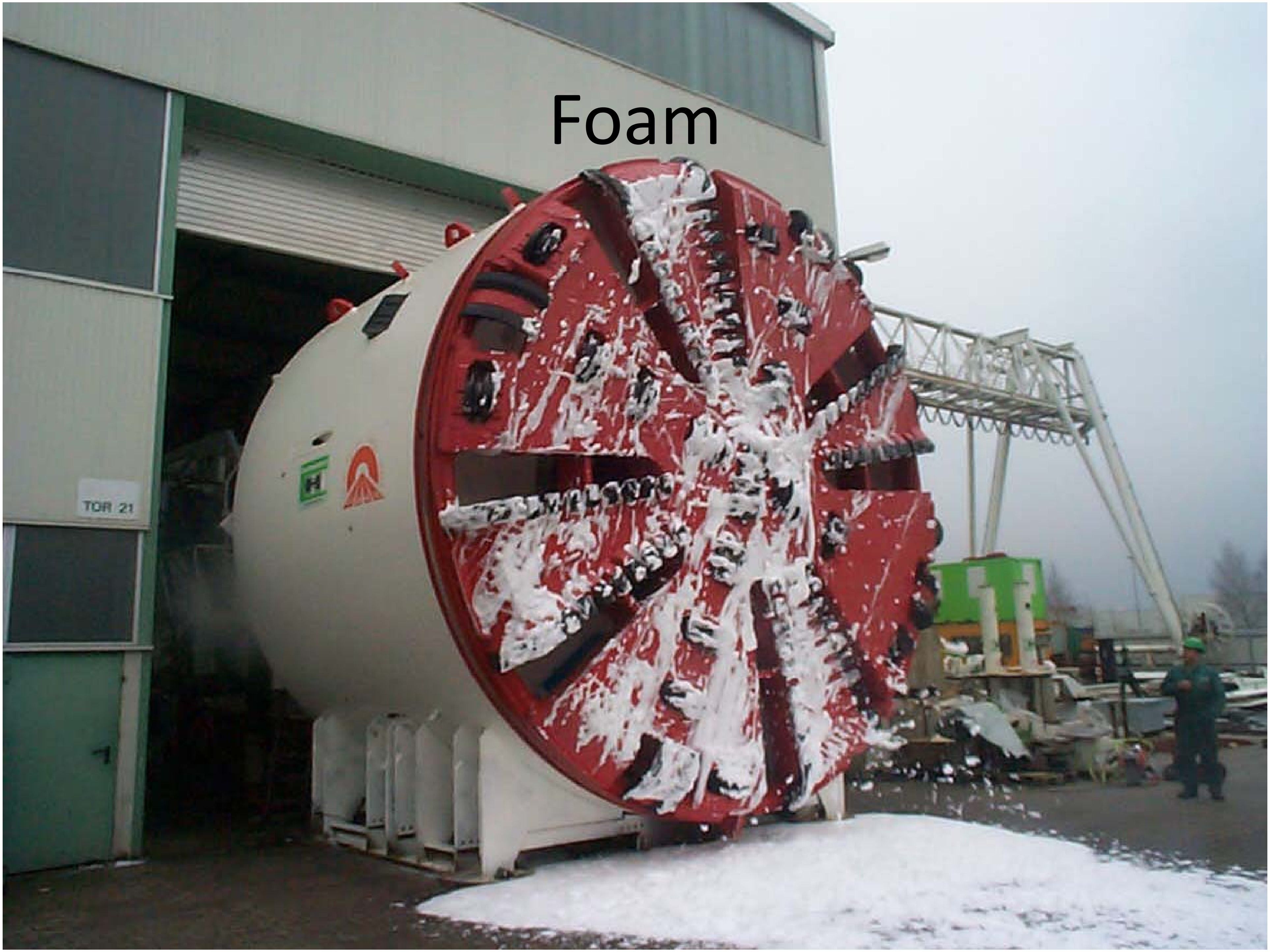
TUNNELING
FOR DELHI METRO

Rock Tunnel Boring Machine

Tunnel Equipment

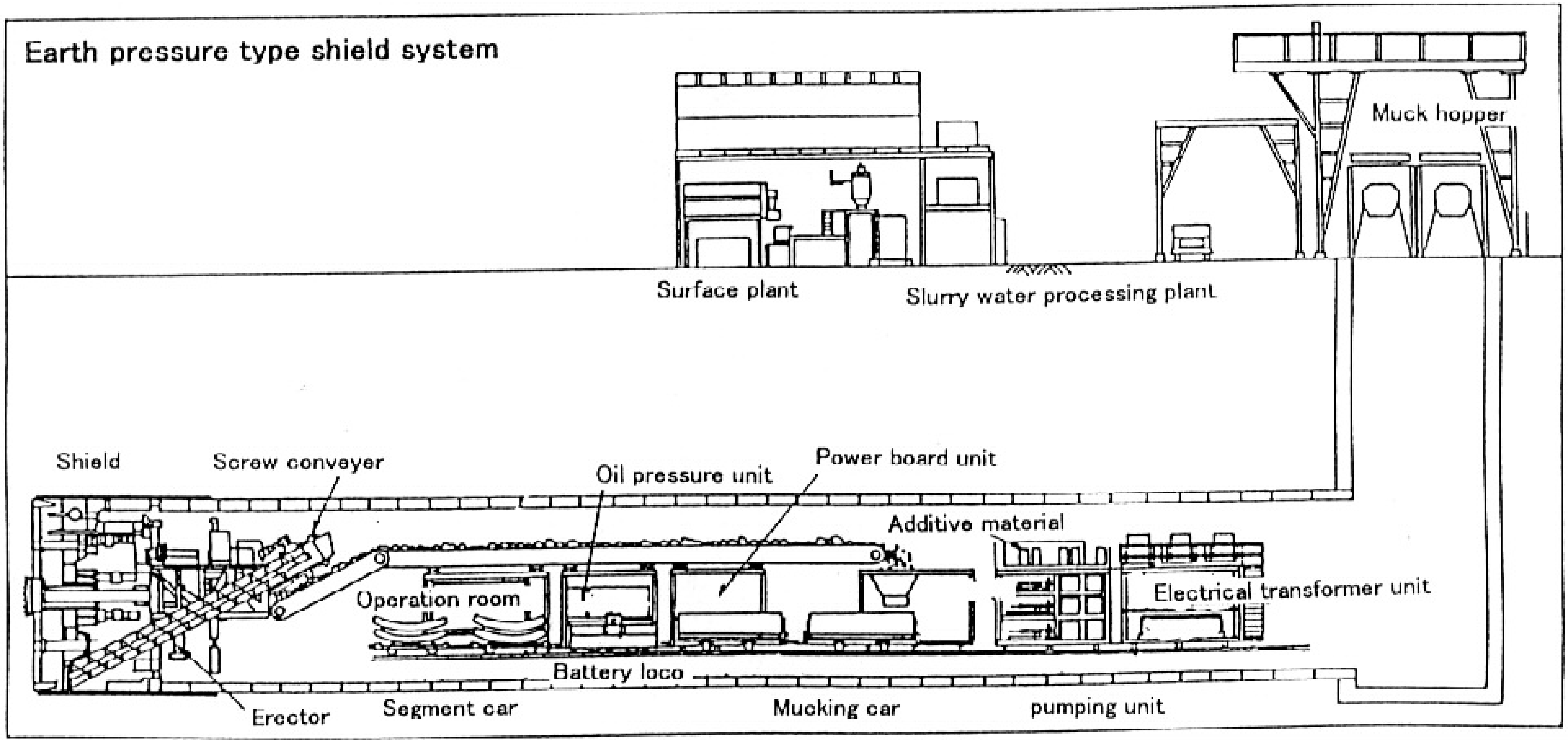
TBM Cutterhead

Foam

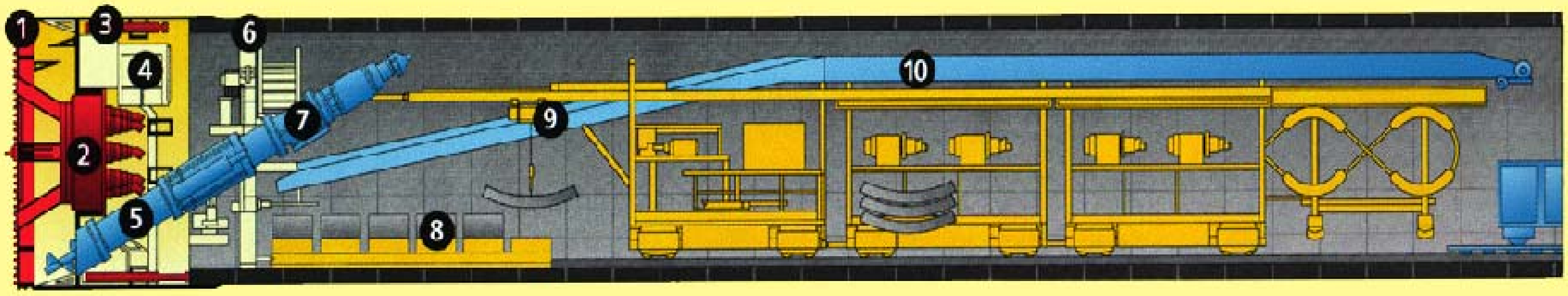


Tunnel Boring Method

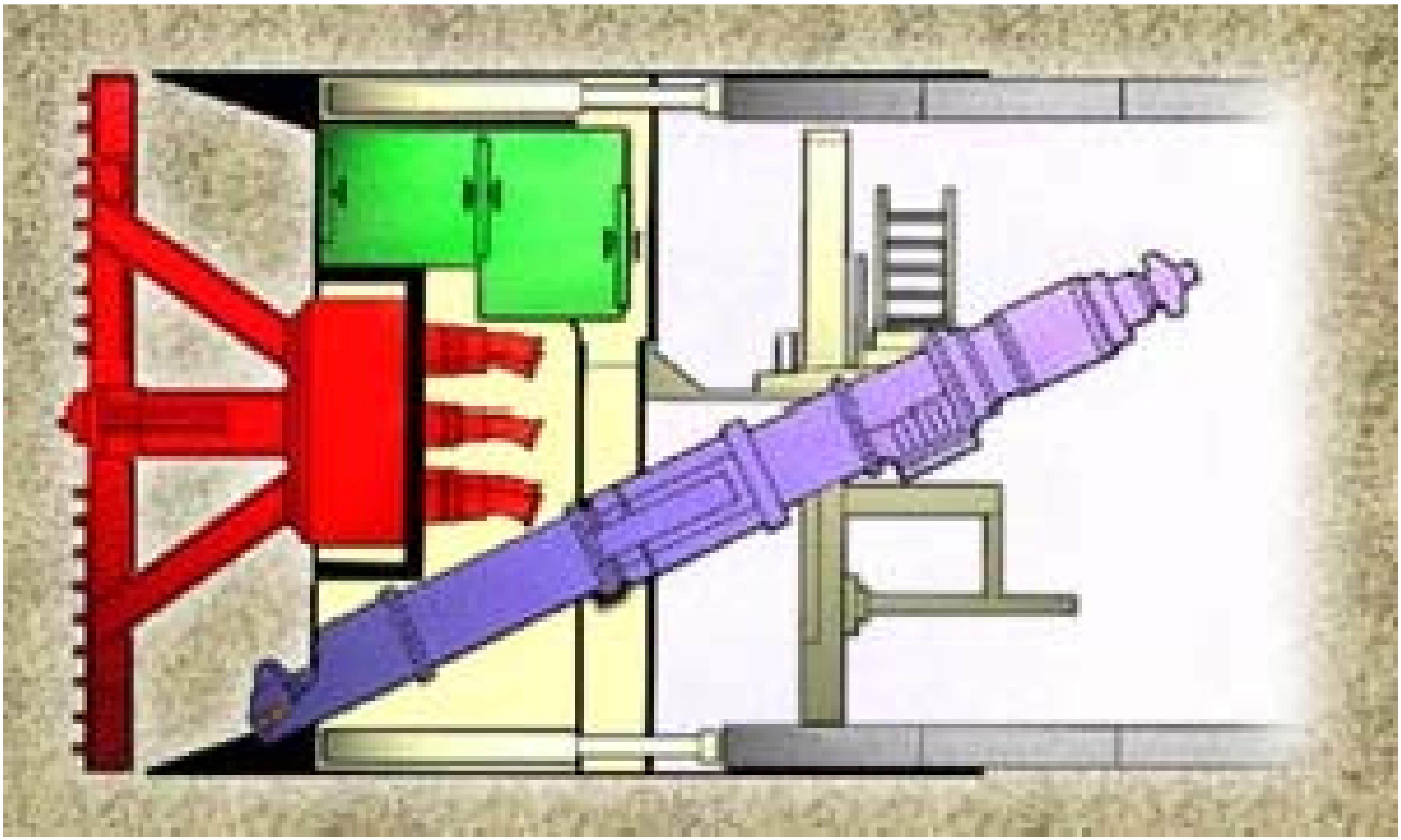
Working Arrangement of Tunnel Boring Machine



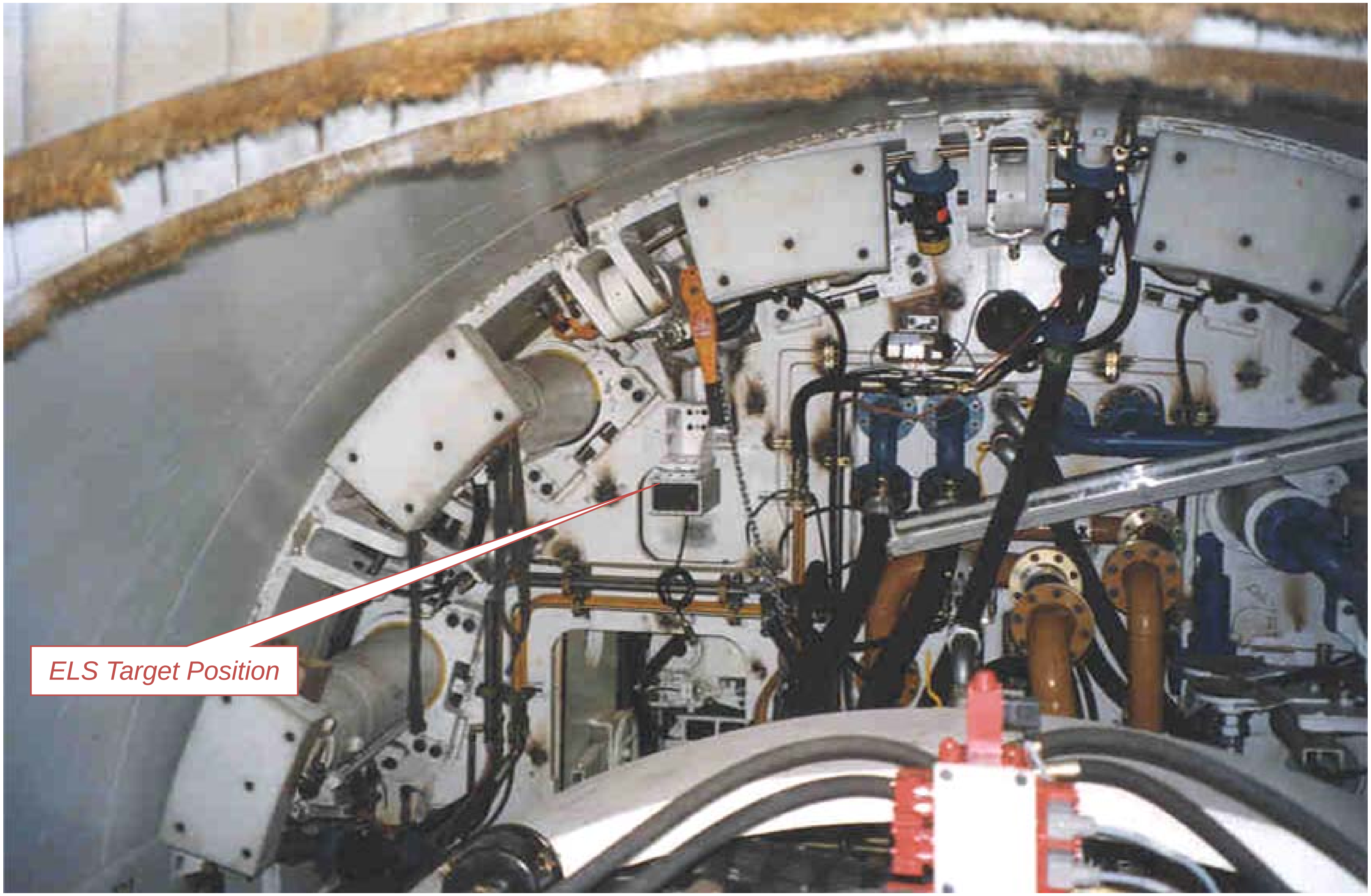
EPB Shield



1. Cutting wheel
2. Drive Unit
3. Push cylinder
4. Air lock
5. Screw conveyor
6. Erector
7. Screw conveyor gate
8. Segment handler
9. Segment crane
10. Conveyor



ELS Target in large TBM



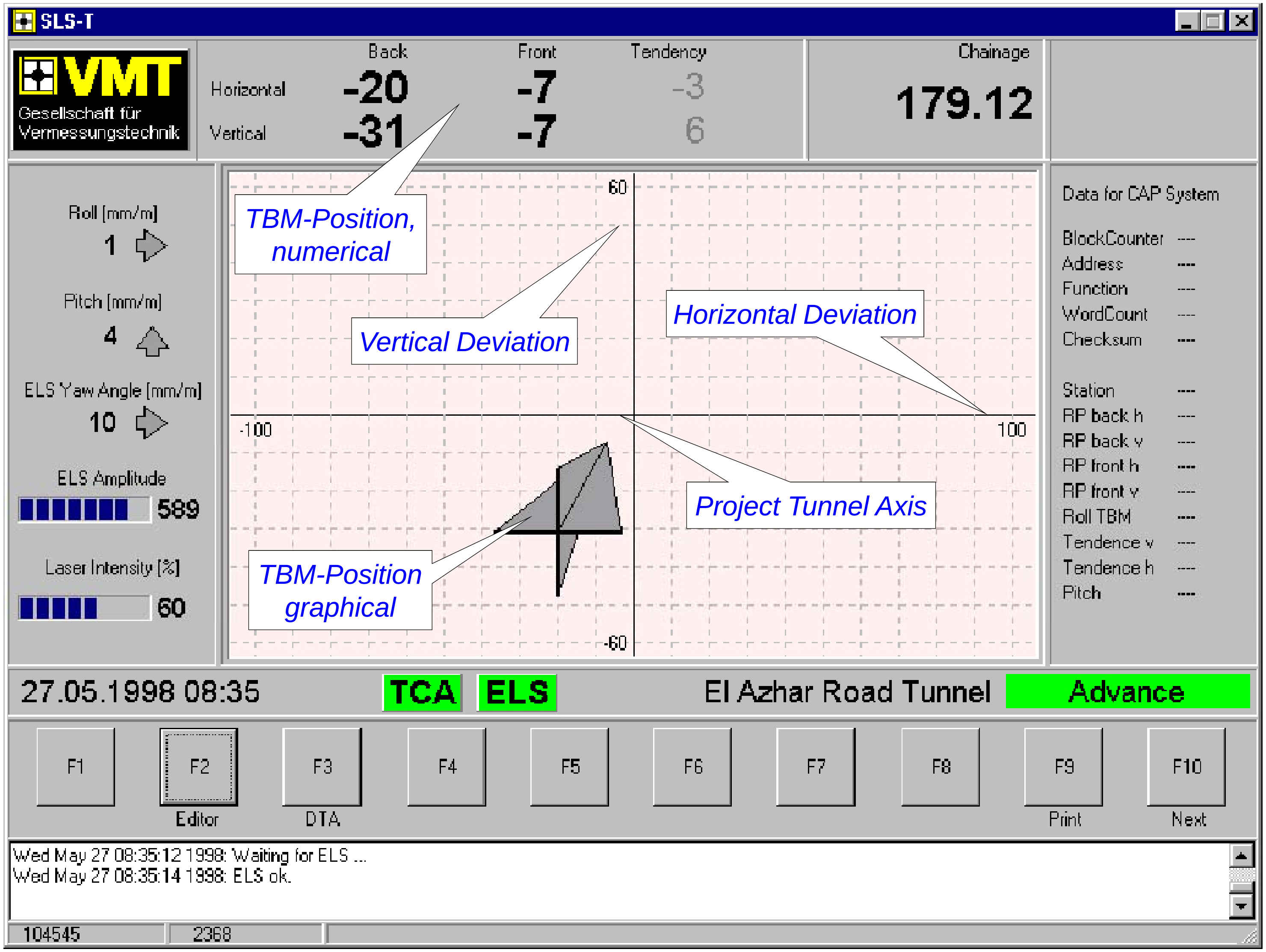
Active Laser Target ELS

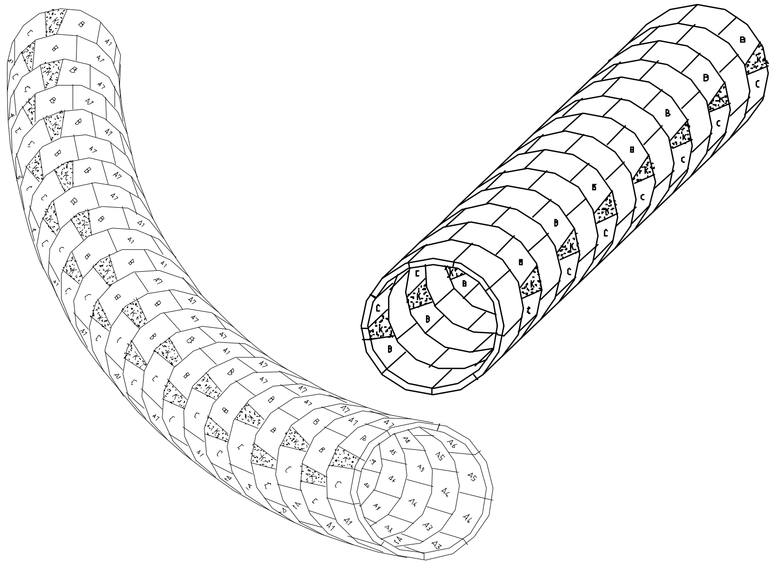
- ➔ **Measurement of precise centre of the laser spot position in X and Y and the horizontal angle of incidence of the laser beam at the target screen**
- ➔ **Pitch and Roll measured by dual axis inclinometer**

Laser Theodolite

- ➔ **Servo Motor controlled Leica TCA 1103 with ATR**
- ➔ **Built in GUS74 Laser**
- ➔ **Angle and Distance measurement to Active Target and Backsight prisms**

Machine Position Display



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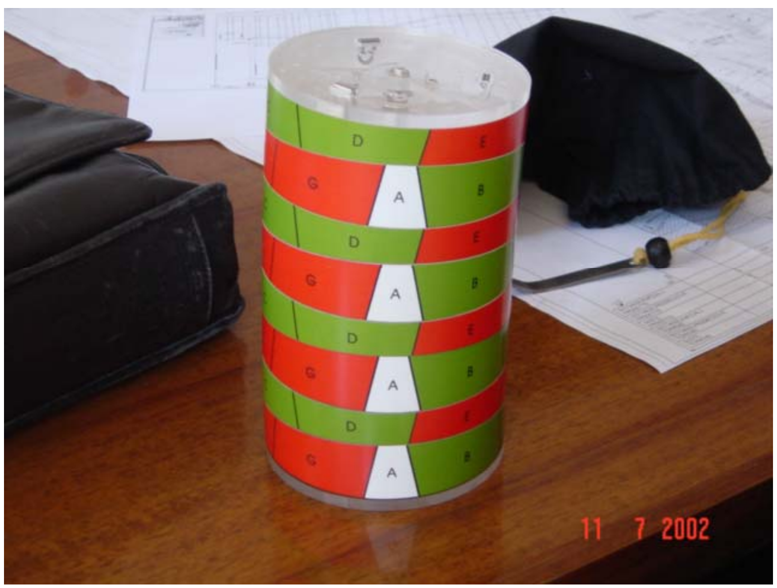
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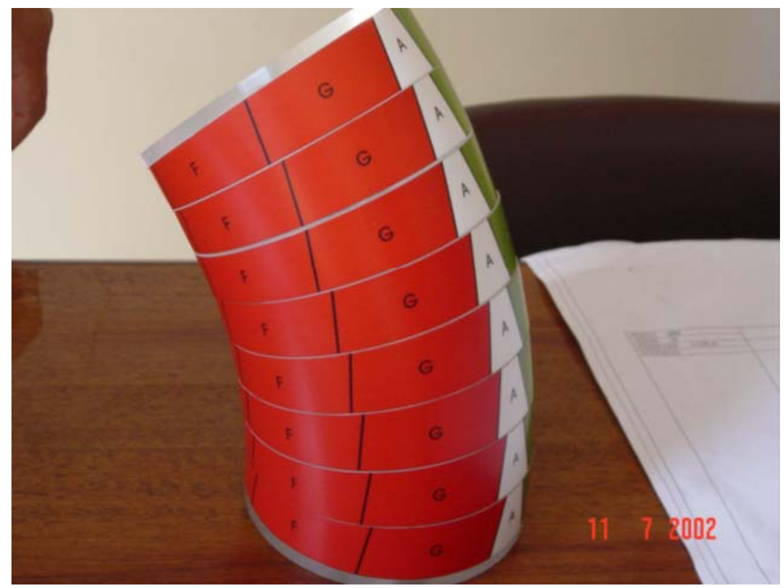
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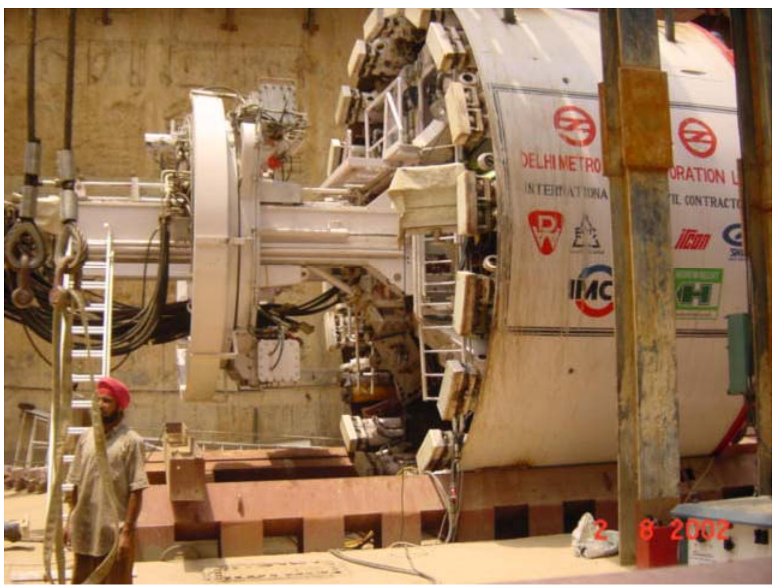
IMCC


26 6 2002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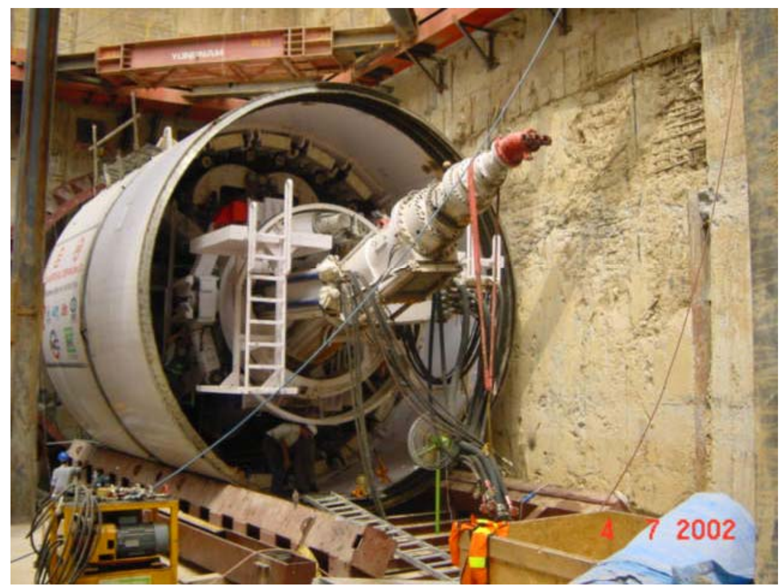
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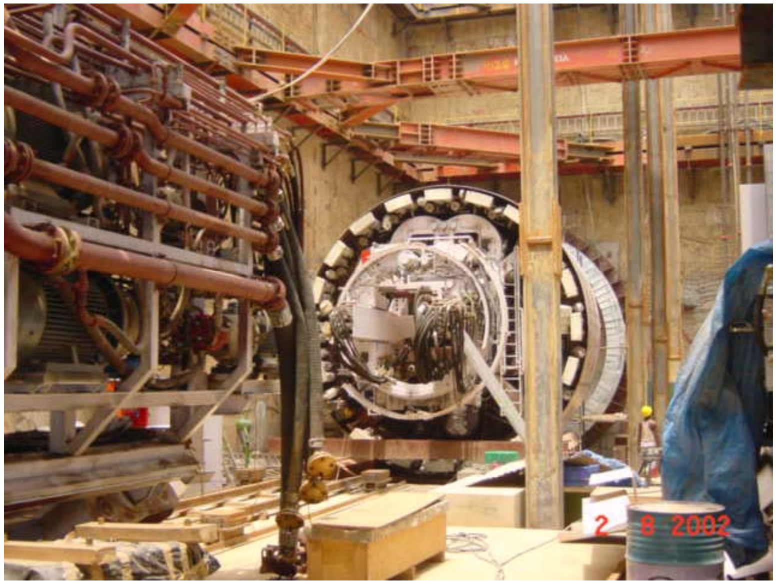
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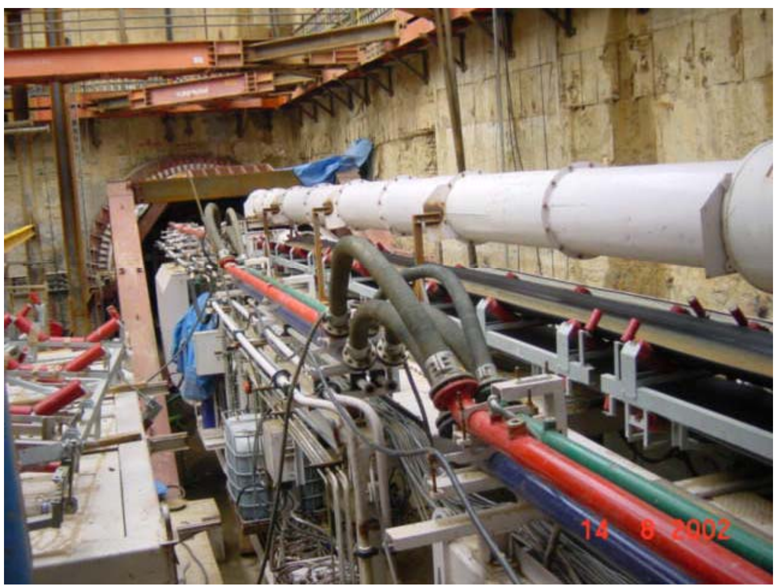
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20 12 2002

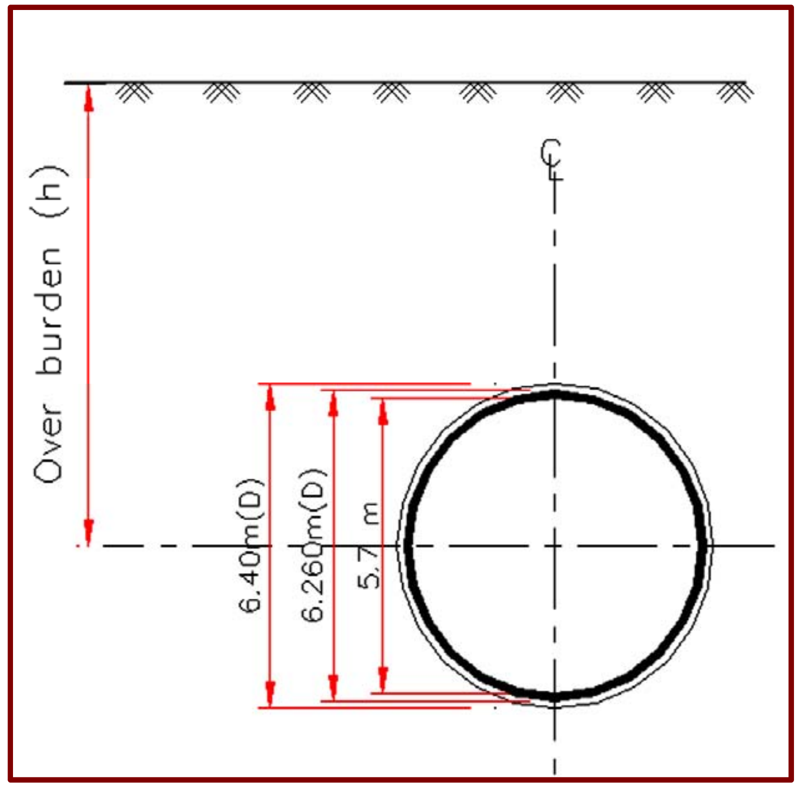
21 12 2002

3 1 2003

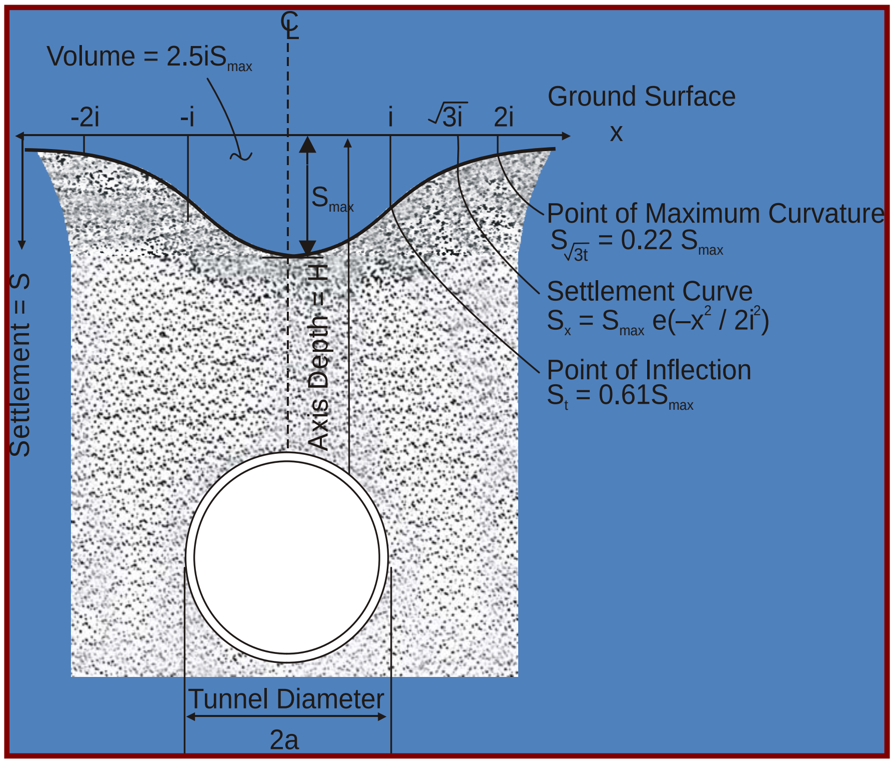
8 1 2003

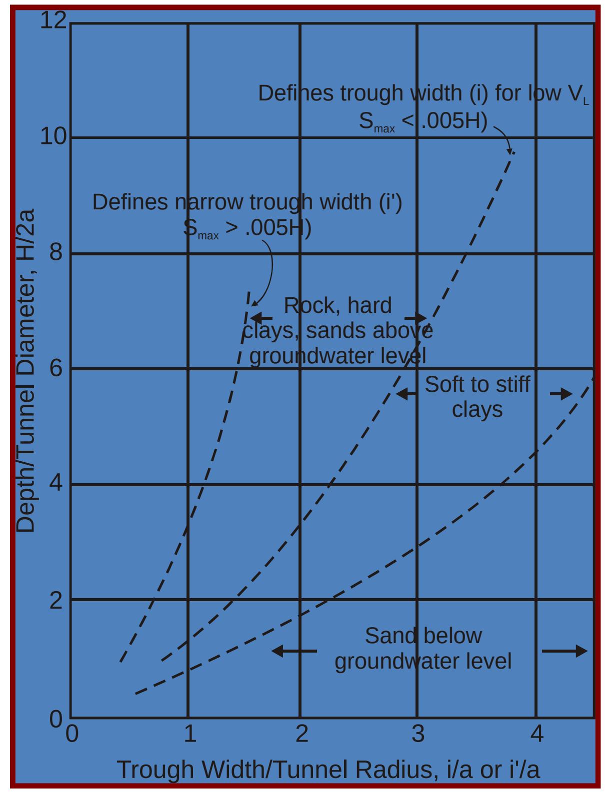
Ground Surface Settlement

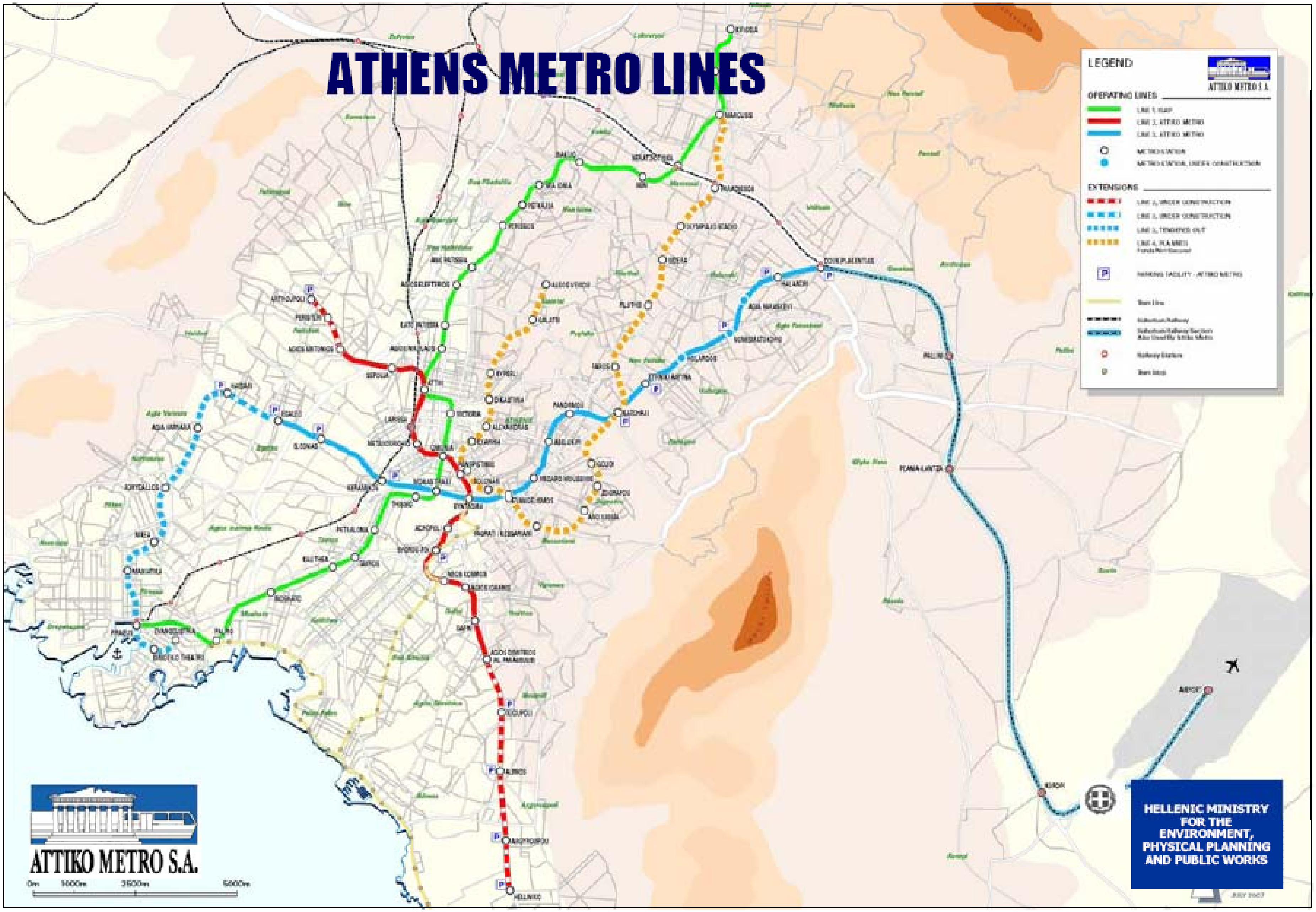
- Immediate Ground Movement
  - Due to Face Loss and Redistribution of In-situ Stresses
- Long-term
  - Due to Consolidation



Geometry of Settlement Trough






ATHENS METRO LINES
LEGEND
OPERATING LINES
EXTENSIONS
ATTIKO METRO S.A.
HELLENIC MINISTRY FOR THE ENVIRONMENT, PHYSICAL PLANNING AND PUBLIC WORKS

CONSTRUCTION METHODS
& TUNNEL BORING MACHINES

For the construction of the underground Metro stations and tunnels, up-to-date methods, which ensured safe and rapid completion of the Project, were applied. The Project construction methods and the Tunnel Boring Machines were used either separately, or combined one to another, as deemed applicable, always in relation with the geological conditions and the in-situ conditions of the surrounding area.

CONSTRUCTION METHODS

- Underground Conventional Boring Method (New Austrian Tunneling Method - NATM)
- Cut & Cover Method
- Cover & Cut Method

TUNNEL BORING MACHINES

- Full Face Cutterhead Tunnel Boring Machines (TBMs)
- Earth Pressure Balance, Tunnel Boring Machines (EPB)
- Open Face Shield Tunnel Boring Machine (OFS)

CONSTRUCTION METHODS

Conventional Tunnel Boring Method (NATM)

It was used for tunnel boring at soils with poor mechanical characteristics. This method has been applied in 8 stations so far as well as sections of single, double and triple track tunnels as needed.

NATM Tunnels

CONSTRUCTION METHODS

Cut & Cover Method

This method was mainly used for the excavation of the stations of the Project, as well as in a few cases, for the excavation of tunnels at locations where problems were encountered due to poor mechanical characteristics of the soil.

C & C Station – TBM Launching

CONSTRUCTION METHODS

Cover & Cut Method

This method constitutes a variation of the Cut and Cover Method and was used only at SYNTAGMA Station (Line 2) due to the particularity of the area.

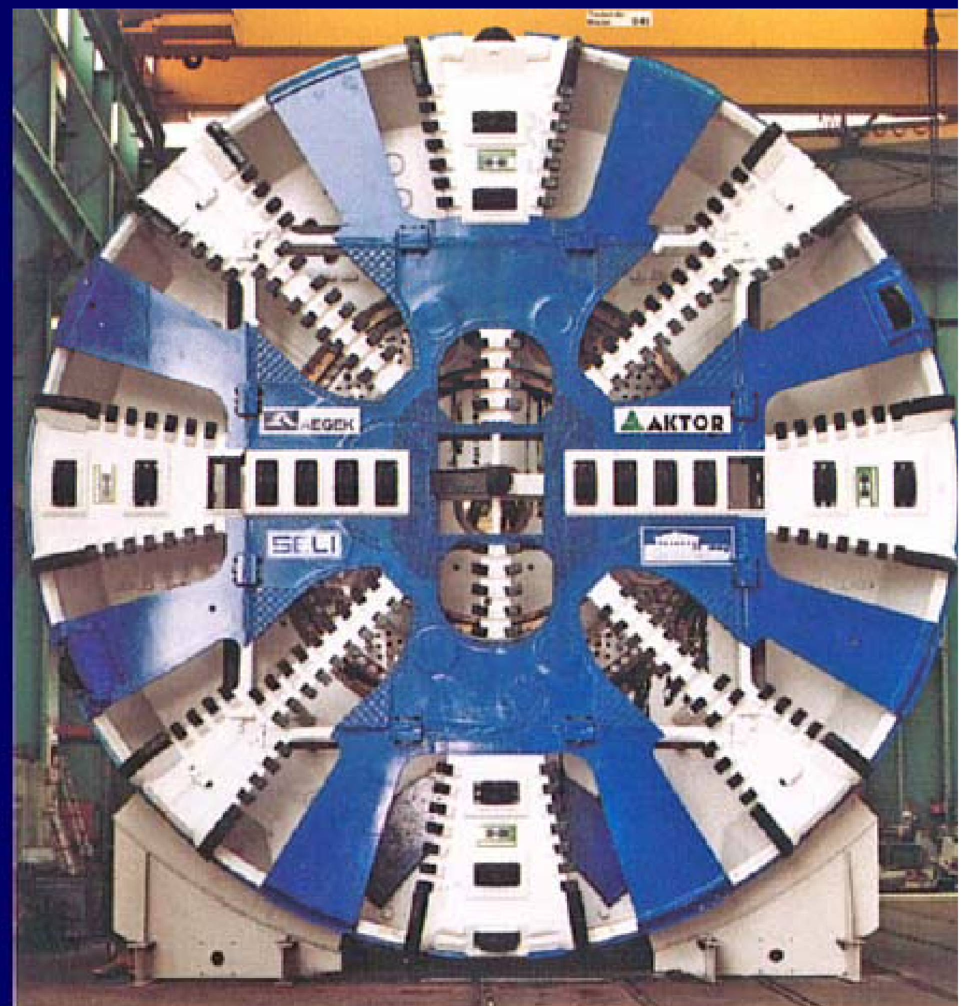
TBM through a NATM Station

TUNNEL BORING MACHINES

ATTIKO METRO S.A

Earth Pressure Balance Machine (EPB)

This method was applied for tunnel boring and construction and, namely, for the construction of 3.4 km in the Line 3 extension to D.Plakentias and is currently being applied in the Line 2 extension to Elliniko (4.8 km).



Elliniko extension – tunnel under construction

Elliniko station breakthrough

Trumpet shaft passing through

TUNNEL BORING MACHINES

ATTIKO METRO S.A

Open Face Shield Tunnel Boring Machine (OFS)

This method was used for tunnel boring and construction and specifically for the construction of Dafni – Ag. Ioannis tunnel section (765m. long) as well as for Anthoupoli – Peristeri tunnel section (910m. long).

Ground Improvement – Risk Mitigation Measures

- Forepoling in advance of the excavation face under sensitive areas.
- Micropiling in the vicinity of selected buildings foundations.
- Tube-a-manchettes / pressure grouting from street level.
- Other (microtunnels umbrella etc.)

Pilot Tunnel – TBM Cutter Head

Ground Improvement – Street Level