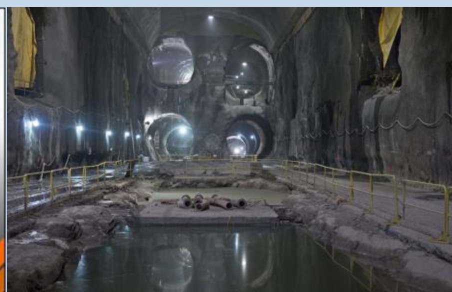
GeoVirginia 2016
Lessons Learned in Geotechnical Engineering
Williamsburg VA
October 10 - October 12

Geotechnical Investigations for Tunneling and Underground Construction Projects, Recommended Considerations Based on Recent Case Histories


Jamal Rostami, PhD, PE
Hadden / Alacer Gold Endowed Chair
Director of Earth Mechanics Institute
Department of Mining Engineering
COLORADO SCHOOL OF MINES
rostami@mines.edu

outline

1. Introduction
2. Difference between Tunnel Gotech and Other applications
3. Tunneling applications, Methods / Machines
4. Some Case Histories
5. Site Investigation for Tunneling
6. Summary

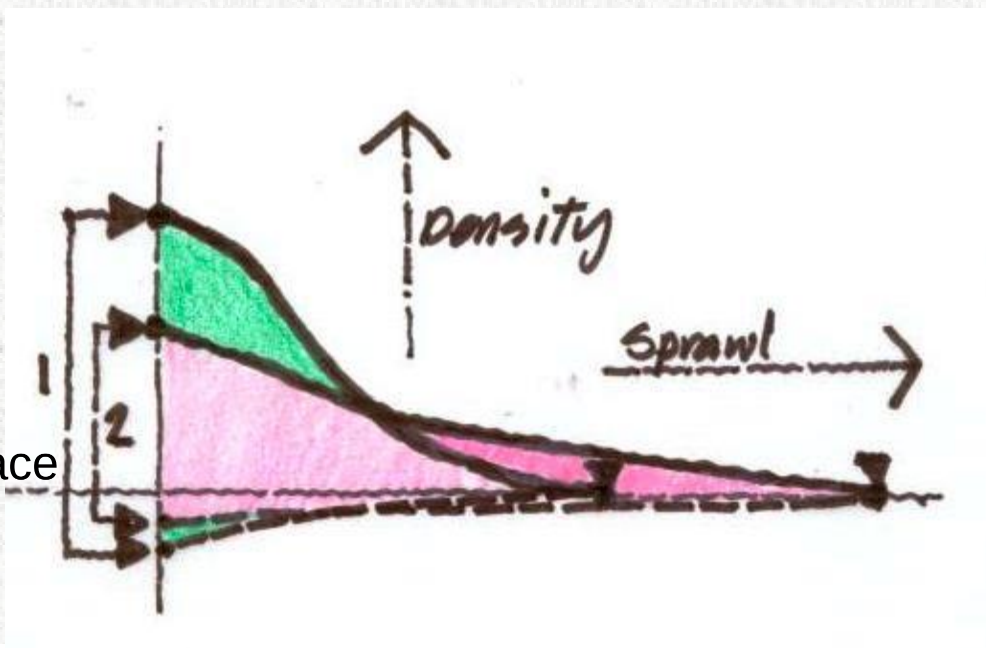
Tunneling and Underground Space

- The use of Tunneling is on the rise on a worldwide basis due to
  - Urbanization,
    - Mass transits i.e. Subway, road tunnels
    - Water and sewer
    - Utility corridors
    - Living space, Parking, etc.
  - Water management
  - Road, Rail, high speed rail
  - Storage, oil/gas/water, Other
  - Defense and Misc.

Will we move to denser sustainable urban use?

1. Denser urban use more typical of urban areas developed prior to the car
2. Sprawling, less dense cities, more typical of urban areas developed with cars
3. Does sustainability suggests this will change?

surface



Source: Priscilla Nelson

Recent Development in Urbanized life

- When density, climate, or topography induce use



People go underground when uses they desire fit best underground, when severe climate makes the underground desirable, and when earth form (hillsides) create easily exploited opportunities. Most uses have been transportation, parking, shopping

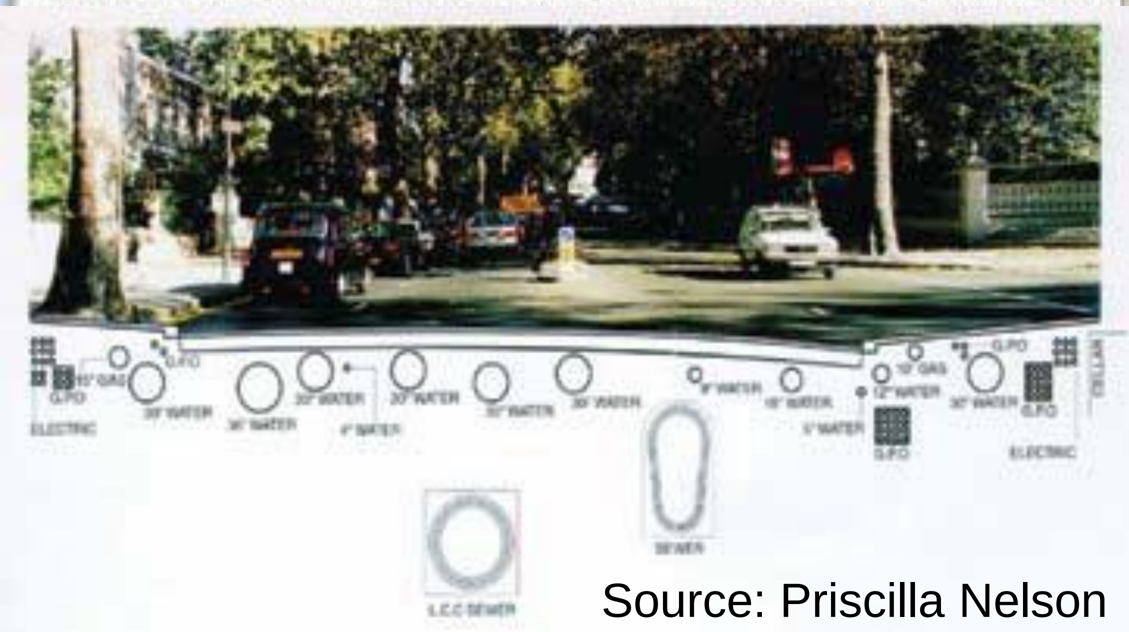

Source: Priscilla Nelson

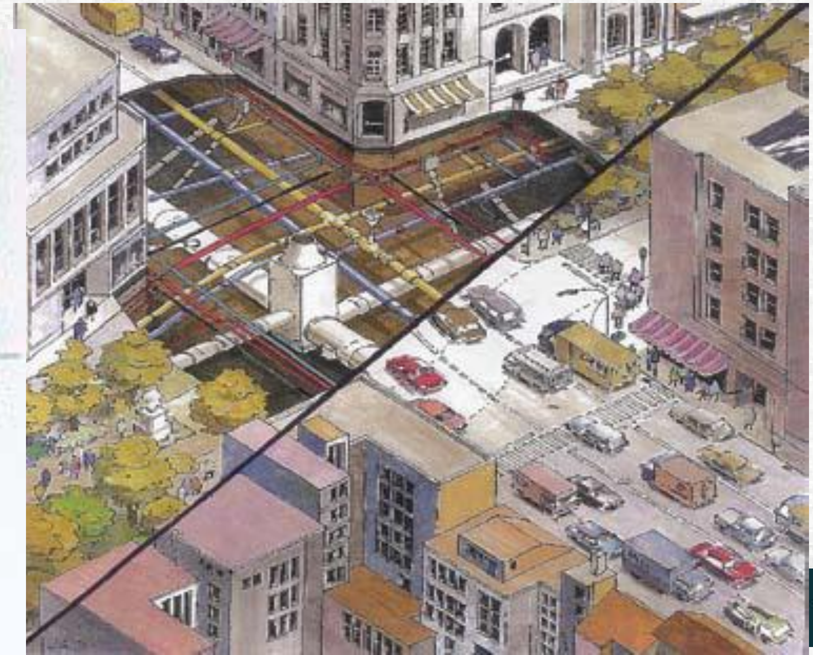
Underground Master Plan

In the UK

Organizations are mandated (and funded) to use geographic information to improve knowledge of their assets in order to

- reduce costs
- ensure regulatory and legislative compliance
- increase customers' satisfaction
- deliver better services
- communicate more effectively

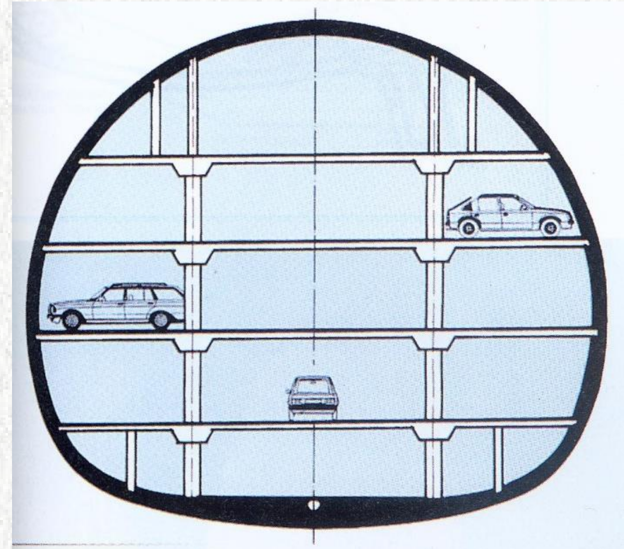


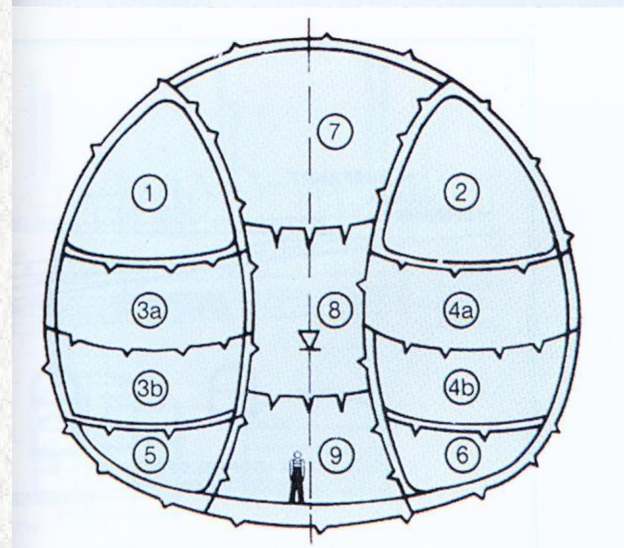


Source: Priscilla Nelson

Applications

- **Underground Parking**
- **Austria**



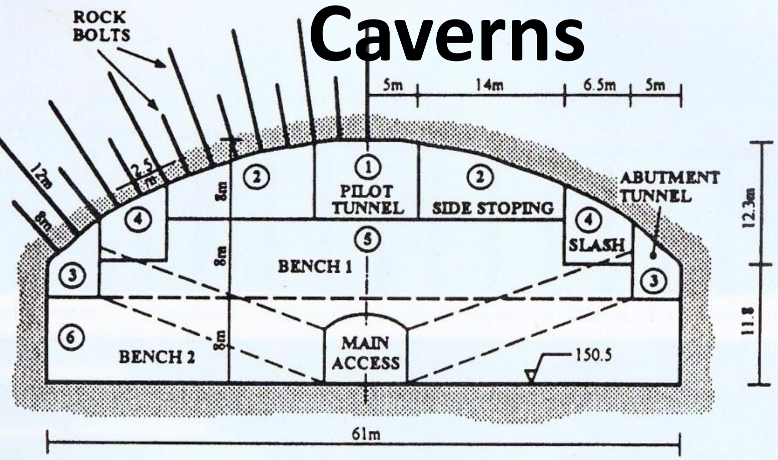


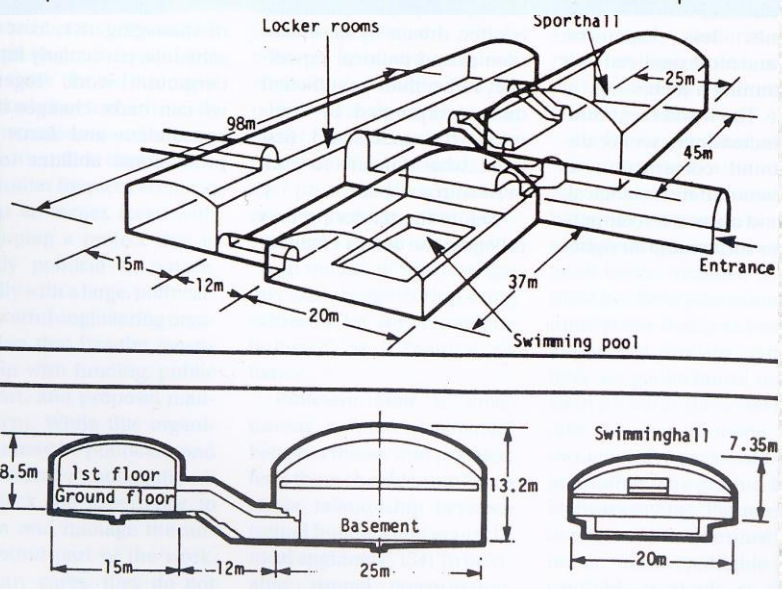
Utilidor

- Amsterdam under the Mahlerlaan

APPLICATIONS

- **Underground Stadium Caverns**

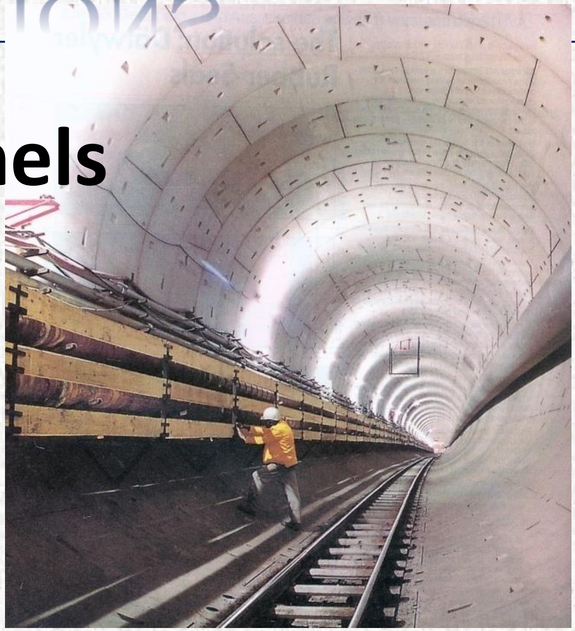


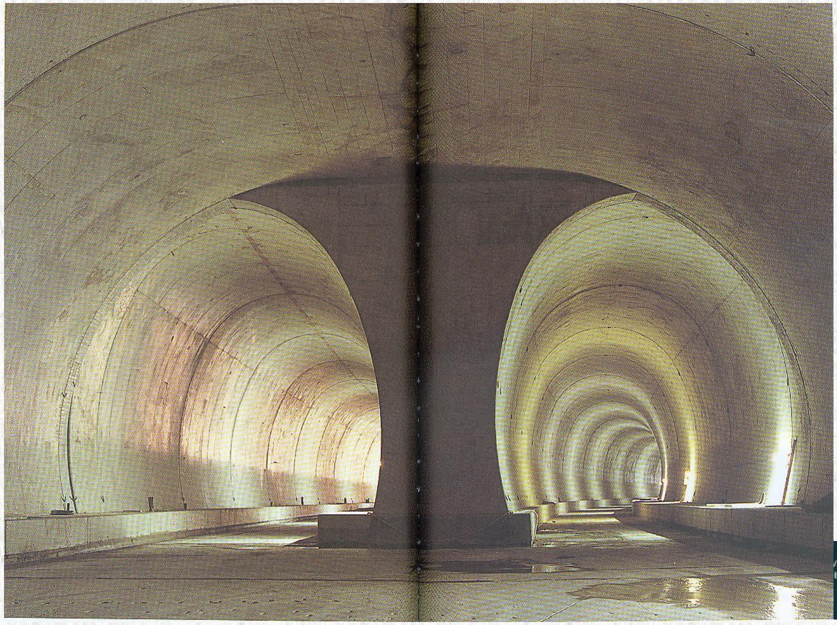


Stormwater management and road tunnel (Smart) Kuala lampur

APPLICATIONS

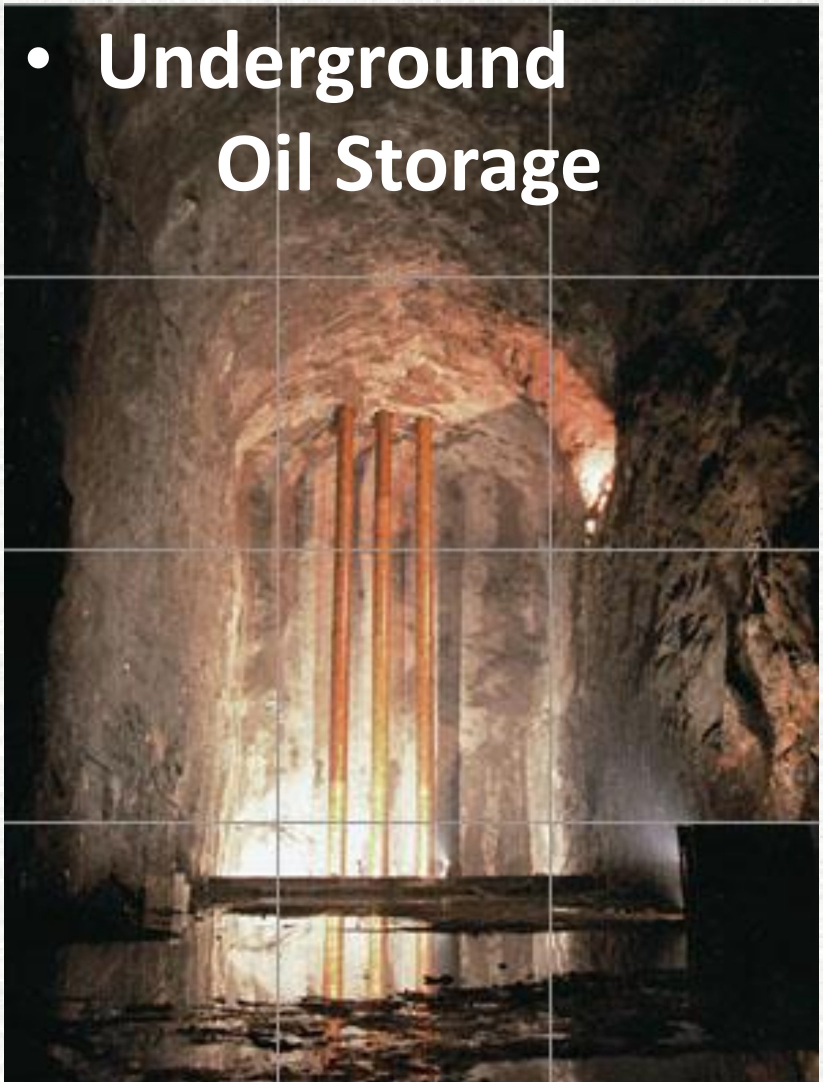
- **Railroad Tunnels**

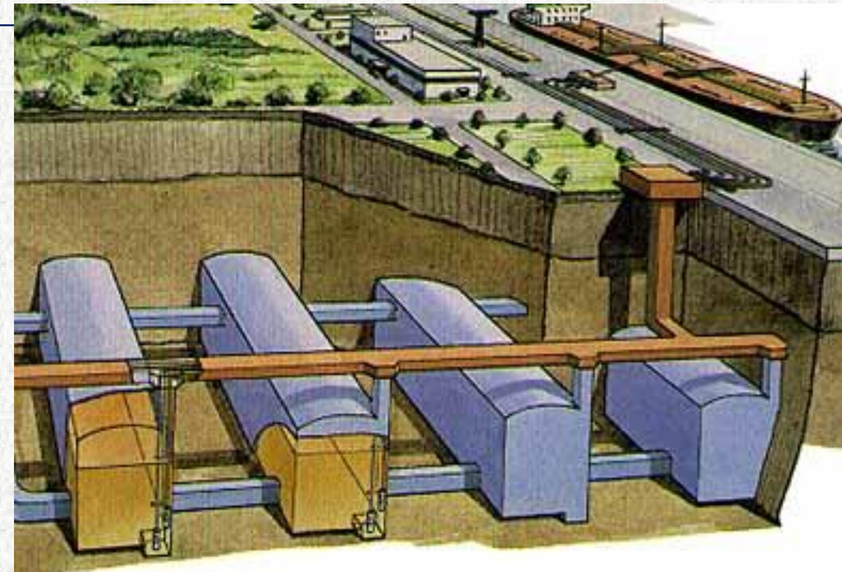




APPLICATIONS

- **Underground Oil Storage**



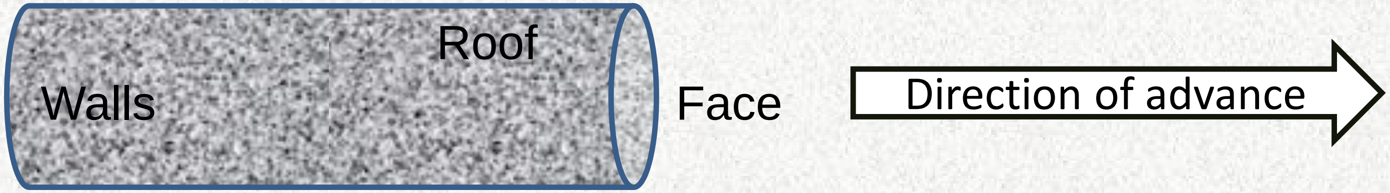


Difference between Tunneling and other Construction Works

- In typical construction the structure is **ON** the ground,
  - Mostly dealing with foundations on soil or rock
- In tunneling, the structure is **IN** the ground for the entire length
  - Dealing with variations in geology/lithology
  - Variability is given, but alignment is mostly unknown except for locations where borings are available, often at high intervals
- Critical to educate owners/public about this issue

Selection of tunneling method

- Based on stability of the ground
  - Roof and walls
    - Stable ground, standing on its own or for sufficient time to install suitable support
    - Unstable ground → shielded tunneling
  - Face
    - Stable face, → Open face
    - Unstable face, → Shielded
  - Groundwater conditions → Pressurized face



Machine Selection

General classification scheme for tunnelling machines (AITES / ITA, Working Group No.14).

Support				Excavation		Reaction Force	Machine	
Location	System			Method	Tool		Category	Type
	Cavity	Face						
None				Partial Face Excavating Machines (PFM)	Various	None or Grippers	Rock Machines	Special Rock Tunnelling Machines - Mobile Miner - Contin uous Miner - Other
Cavity	Shield	None		Full Face Rotat-ing Cutting Head (TBM)	Cutting disk	Grippers		Unshielded TBM Special Unshielded TBM
					Cutting disk/ Cutting bits/ Cutting knives & teeth	Thrust Jacks		Single Shielded TBM (DS-TBM)
					Cutting disk	Grippers and Thrust Jacks		Double Shielded TBM (DS-TBM)
Face and cavity				PFM	Rod header/ Back hoe/ Manual excavation	Thrust Jacks	Soft Ground Machines	Open Shield
		Mechanical		TBM	Cutting bits/ Cutting knives & teeth	Thrust Jacks		Mechanical Supported Closed Shield
				PFM	Road header/Back hoe			Mechanical Supported Open Shield
		Fluid	Compressed Air	TBM	Cutting bits/Cutting knives & teeth			Compressed Air Closed Shield
				PFM	Road header/ Back hoe/ Manual excavation			Compressed Air Open Shield
			Slurry	TBM	Cutting disk/ Cutting bits/ Cutting knives & teeth			Close Slurry Shield – Slurry Shield – SS-Hydroshield
				PFM	Road header/Back hoe			Open Slurry Shield – Special Open - Slurry Shields
			Earth Pres-sure Balance	TBM	Cutting disk/ Cutting bits/ Cutting knives & teeth			Earth Pressure Balance Shield - EPBS Special EPBS
	None or fluid	None or slurry or Earth Press. Balance						Combined Shield - Mix Shield - Polishield

TBMs

Shields

Closed Face

Conventional Tunneling by Drill and Blast

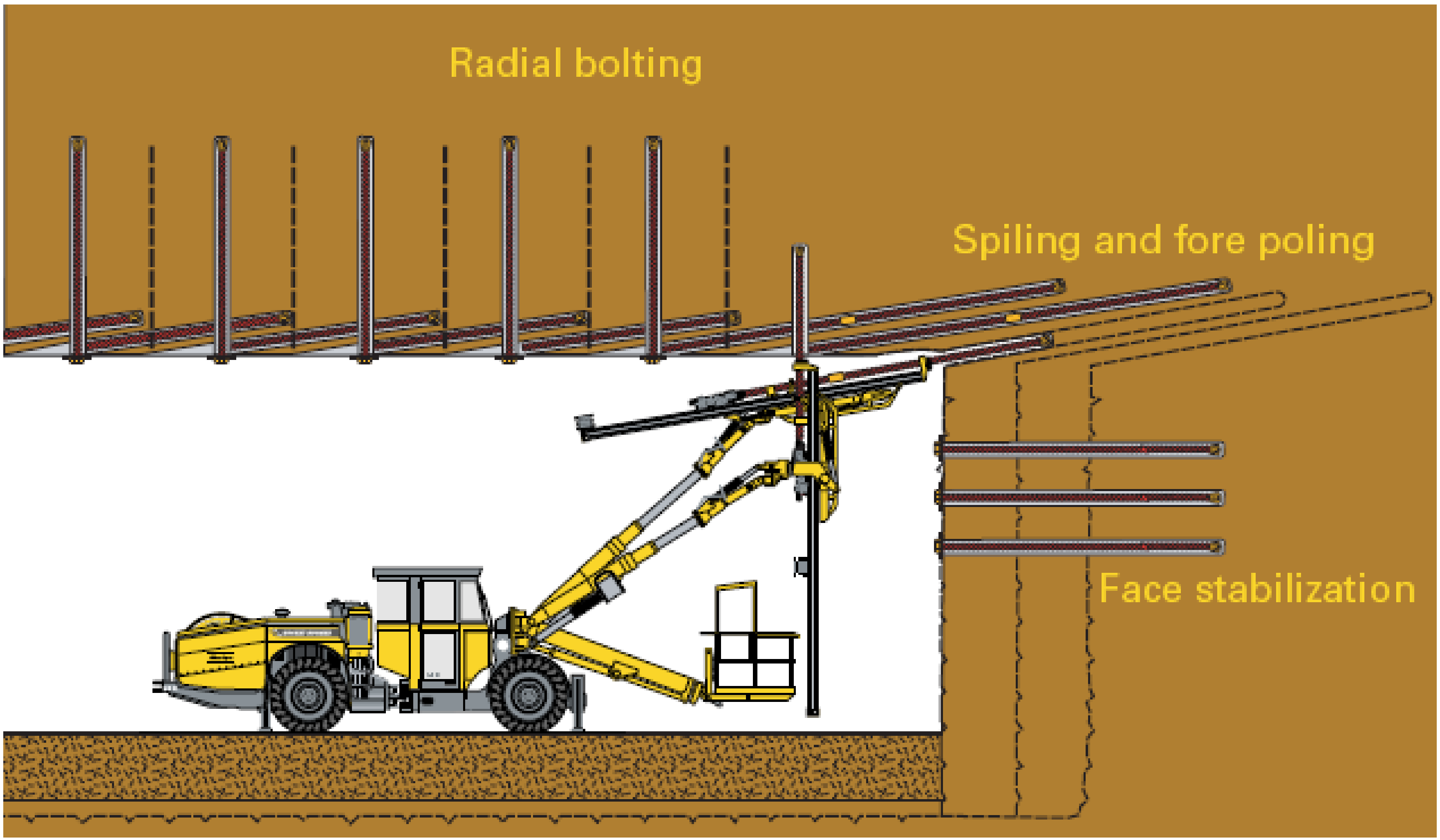
Atlas Copco Face Drilling Manual

Drilling Equipment

Atlas Copco Face Drilling Manual

Ground Control, Roof Bolting Equipment

- Jackleg / Jumbo Drills



Atlas Copco Face Drilling Manual

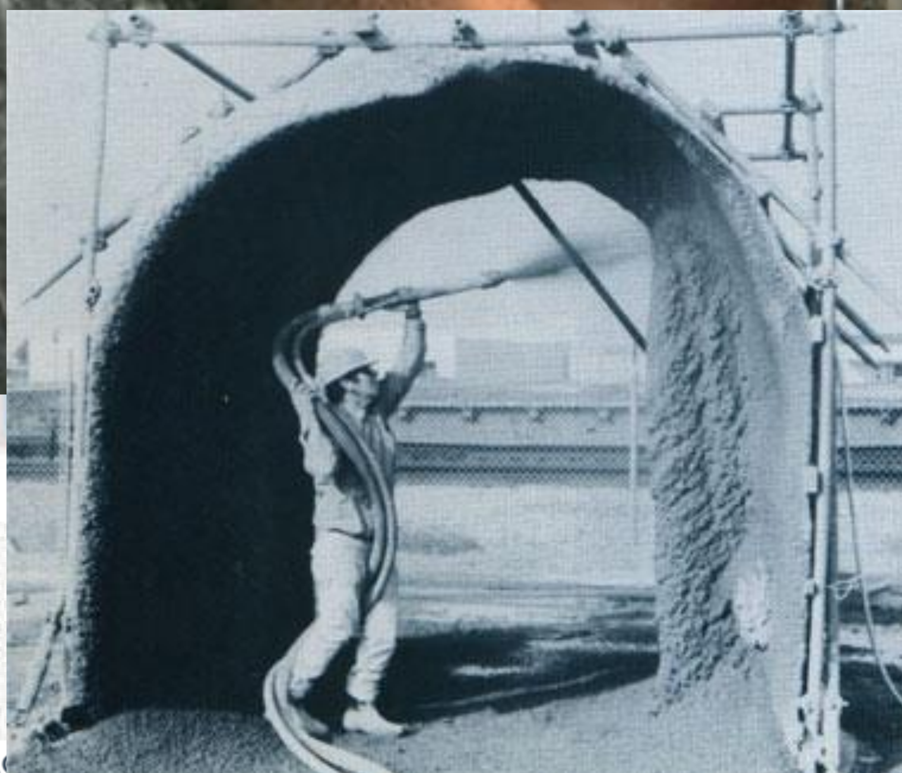
Ground Support

- This goes along with Rock Mass Classification systems RMR or Q

Excavation class *	2-X-F	3-X-F	4-X-F	5-X-F	6-X-F	7-X-F	7-X-F1
Rock Class	Good rock	Fair rock	Poor	Poor	Very Poor	Very Poor	
Rock mass behaviour	From stable to local instability		Structural weakness and/or insufficient interlock between blocks			Squeezing ground: stress exceed rock strength	
	Minor problem	Local overbreak	Friable			Squeezing	Hvy. Squeezing
Shotcrete	5 cm	10 cm	15 cm	15 cm	20 cm	25 cm	25 cm
Wire mesh (layers)	0	1	1	1	1	2	2
Steel Ribs	no	no	no	no	yes	yes	yes
Radial Rock bolts 4 -6 m in length		Cement grouted (S/N bolts)	Swellex Mn 24		Self Drilling Rockbolts		
Front Consolidation	(Spiling steel pipe 4 m long, 10-30 pcs) (Pipe roofing, 15 m long, 20-25 pcs)				Spiling & Pipe Roofing		
Round length (top heading)	3,0-4,0m	2,2-3,0m	1,7-2,2m	1,3-1,7m	1,0-1,3m	0,8-1,0m	0,8-1,0m

* Excavation class according to Austrian standard (Norm B 2203/1994)

Shotcrete

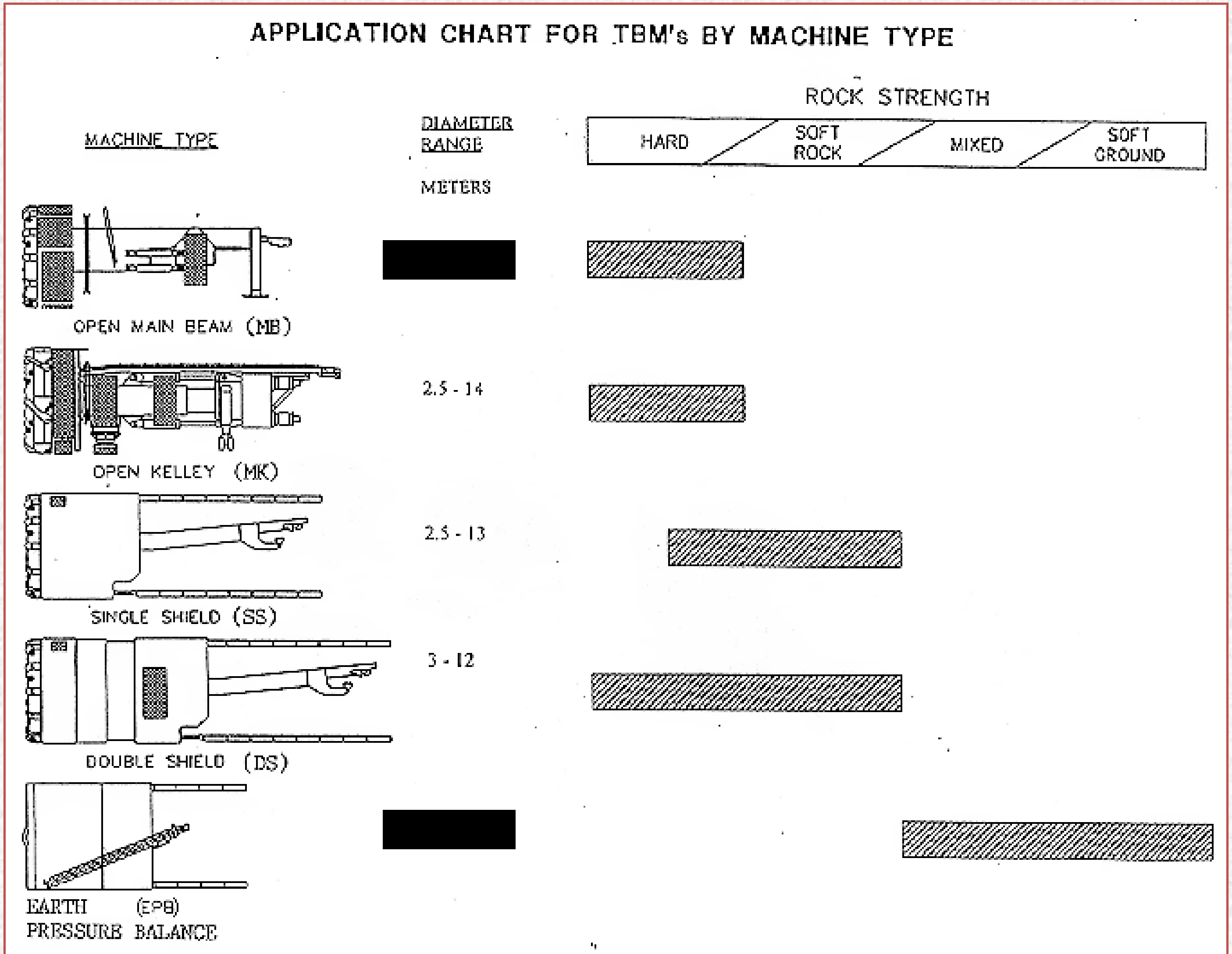


Ground Support

- Final Lining, Cast In Place (CIP) concrete

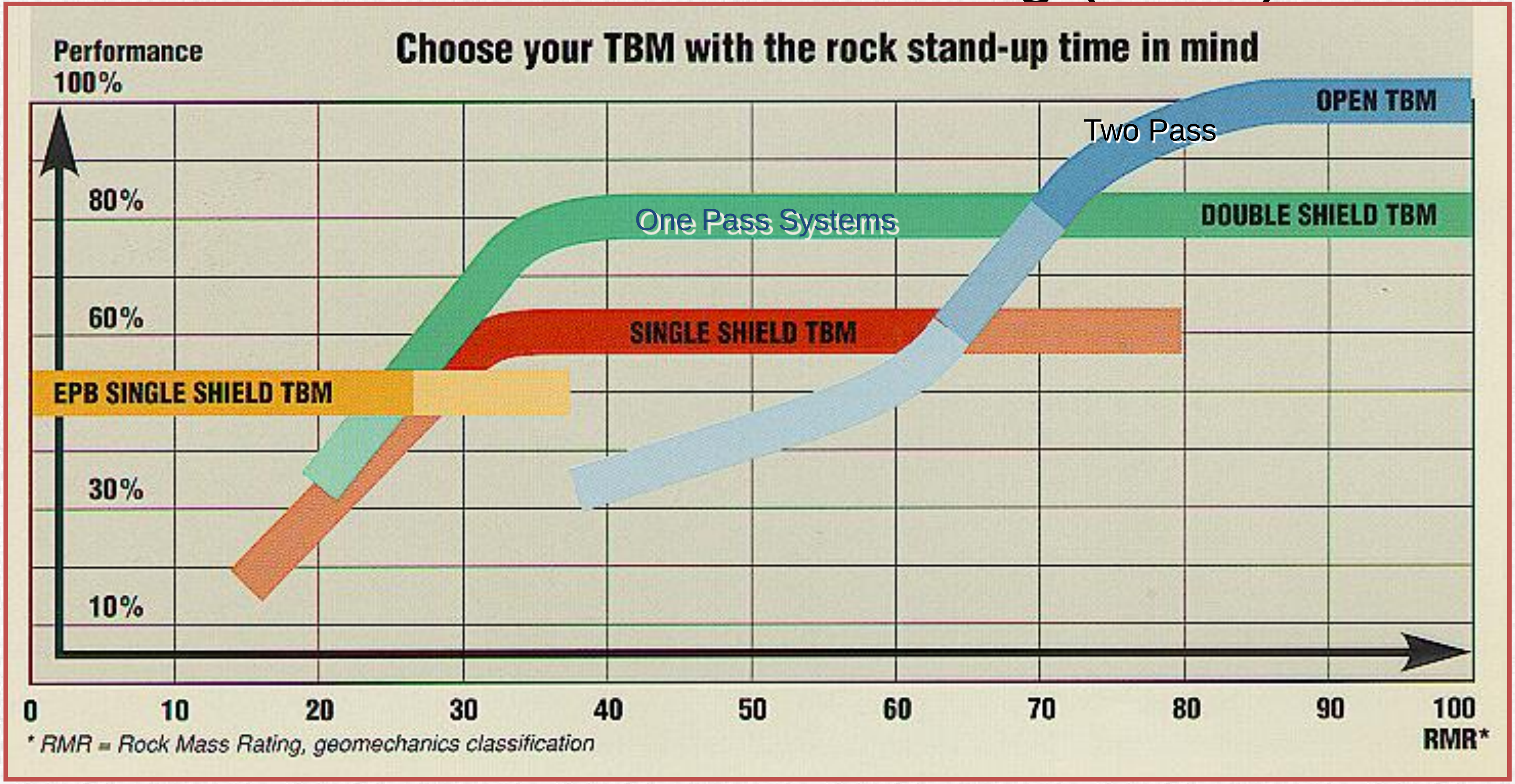
Partial Face Machine, Roadheader

TBM Selection

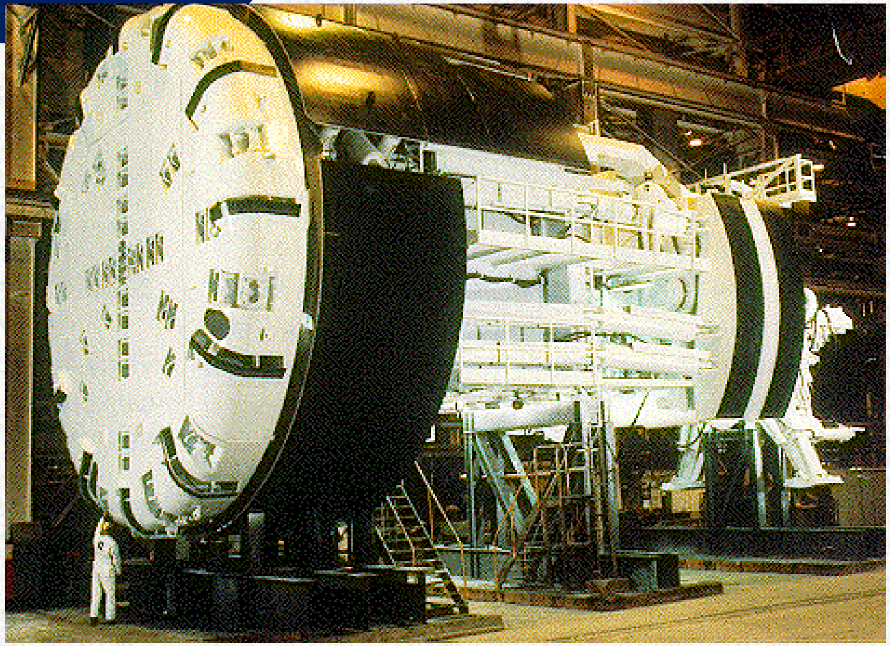


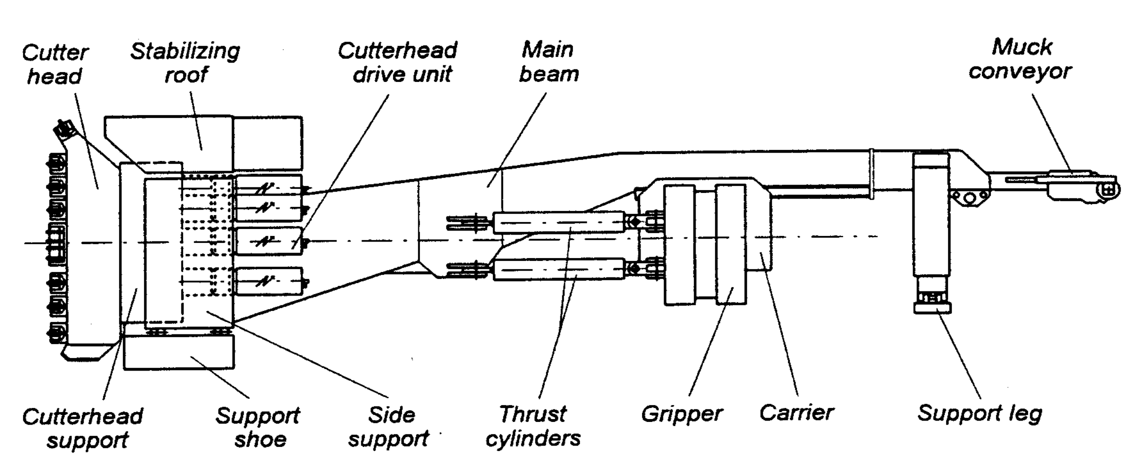
Machine selection as a function of rock mass

- Function of Rock Mass Rating (RMR)



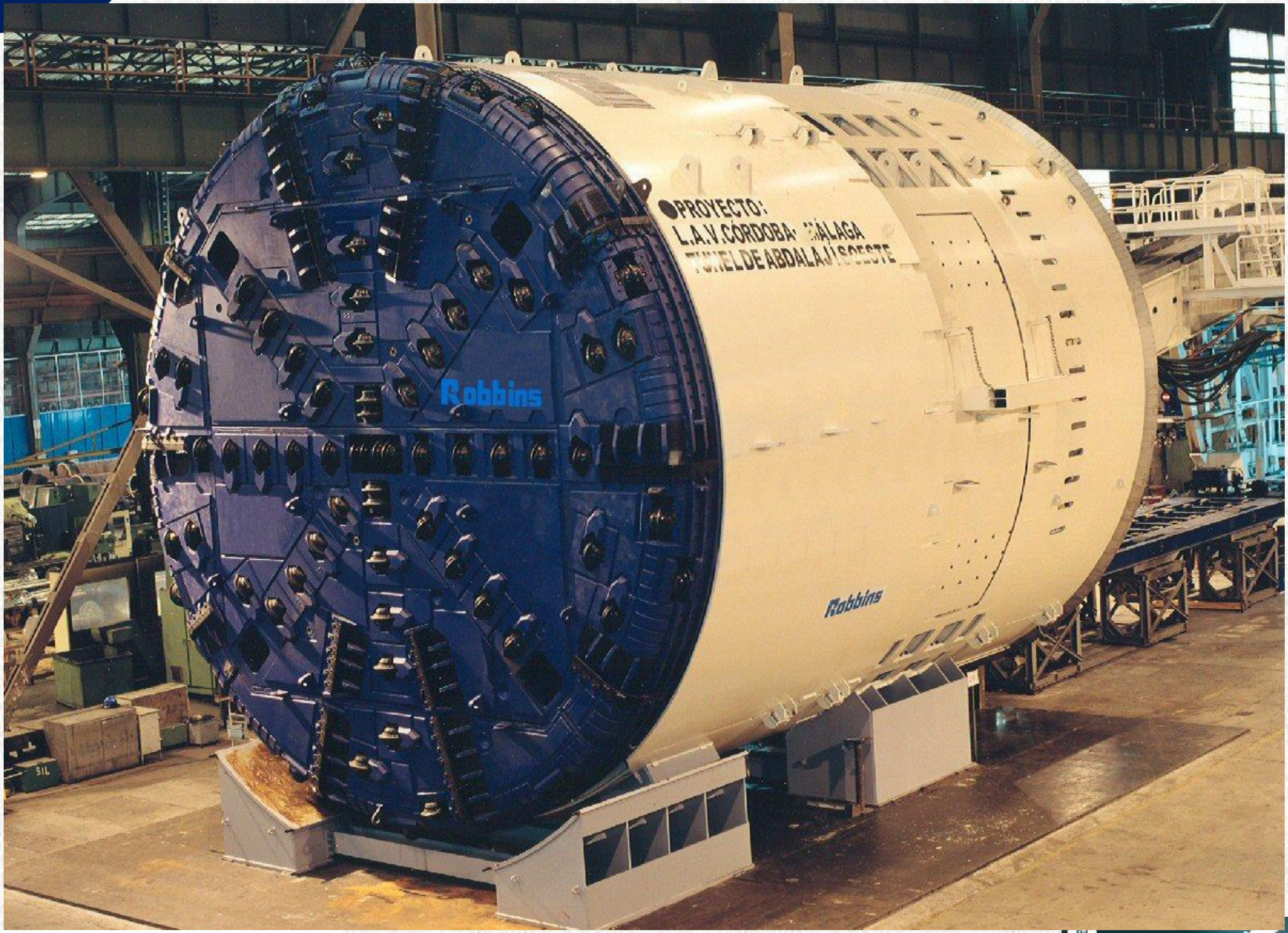
Tunneling by a Main Beam TBM





Main Beam TBM, single grippers

Double-Shield TBM



Shielded TBMs

PDS 740-OS/RM

HDS 1064/660-OS

HDS 660-OS

ADS 248-LS/BV

MDS 356

Shield & LSK 190/300

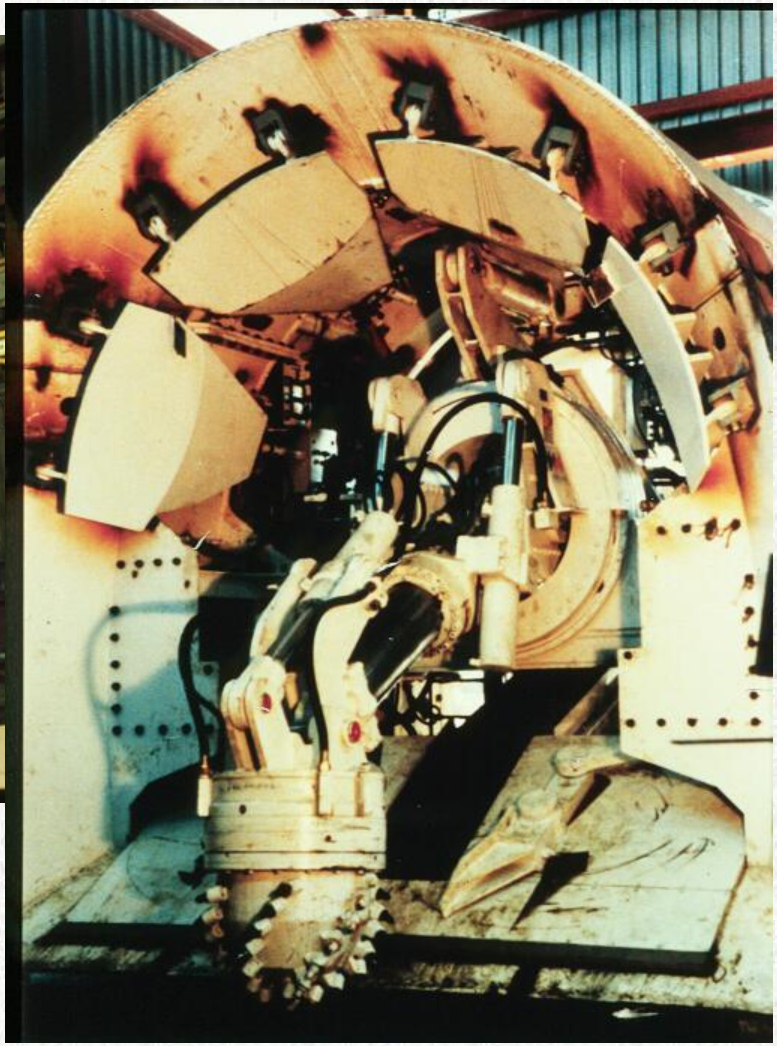
PDS 710-GS/EPB

Telescop Shield

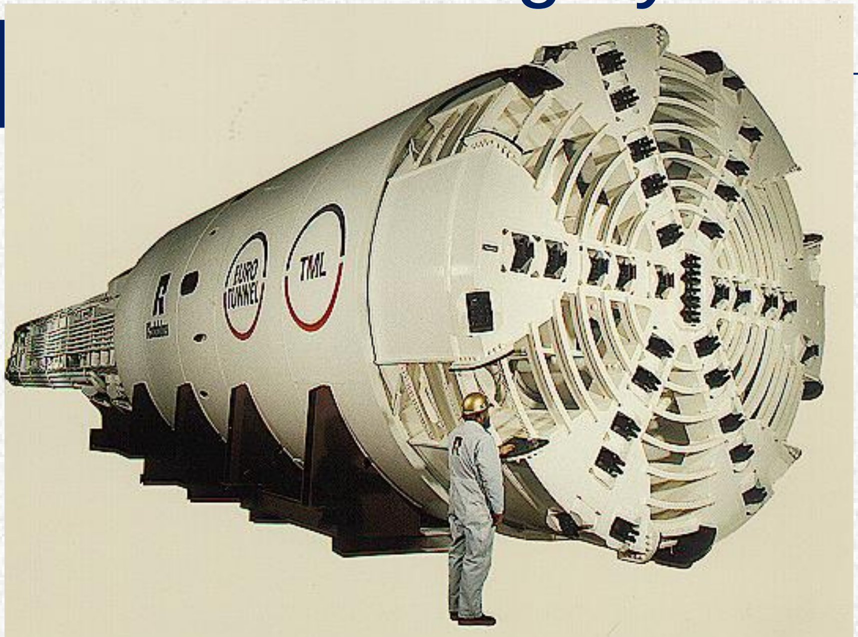
Blade shield

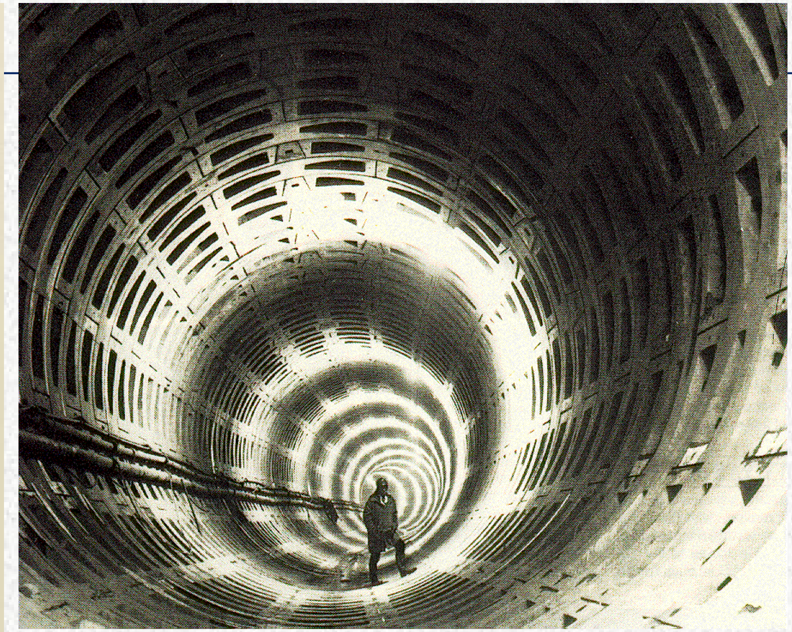
Blade shield

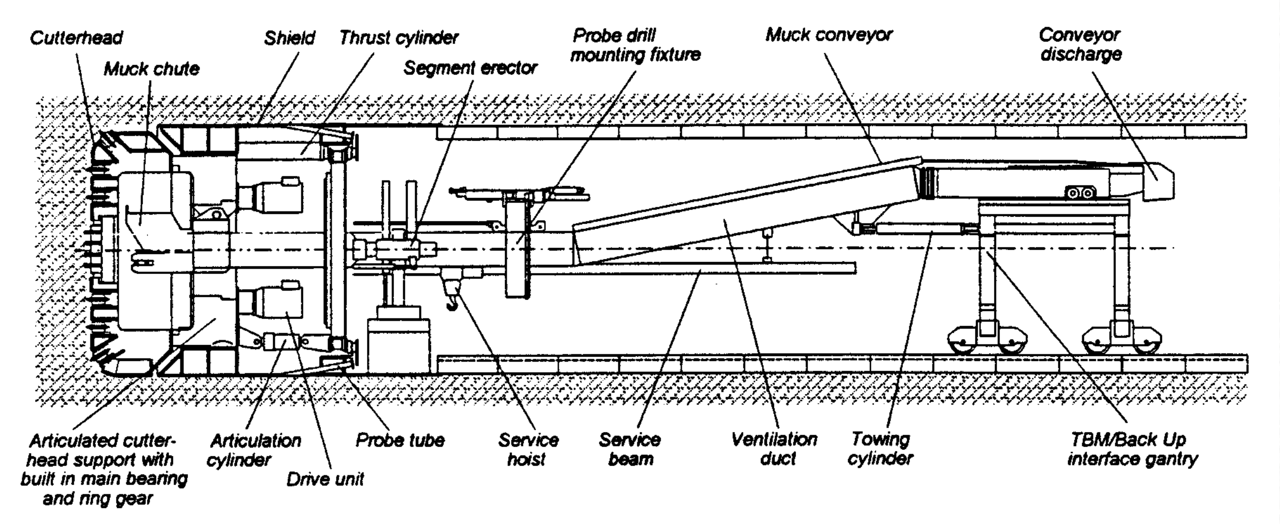
Single Shield, Open Type



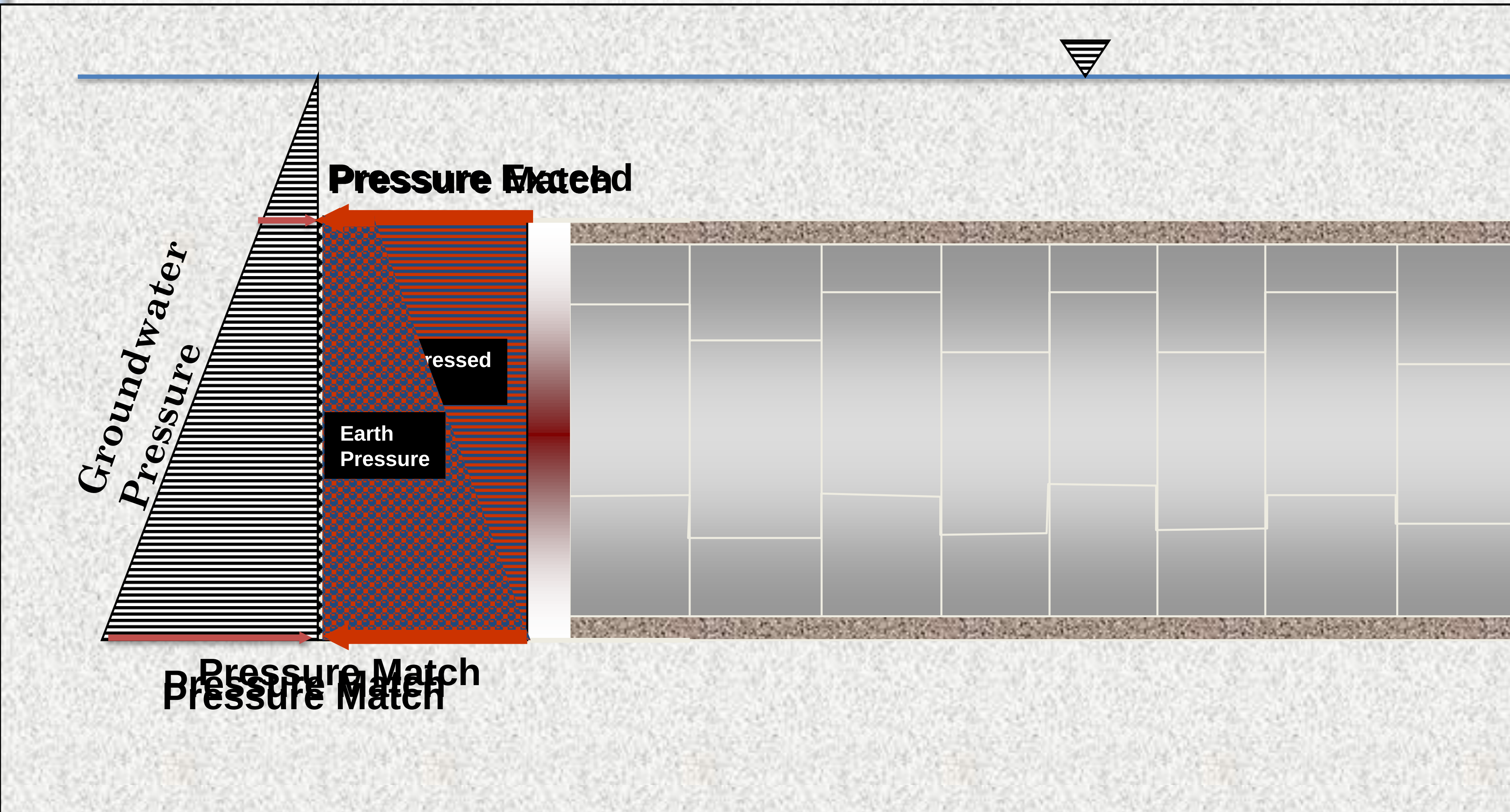
Tunneling by a Shielded TBM





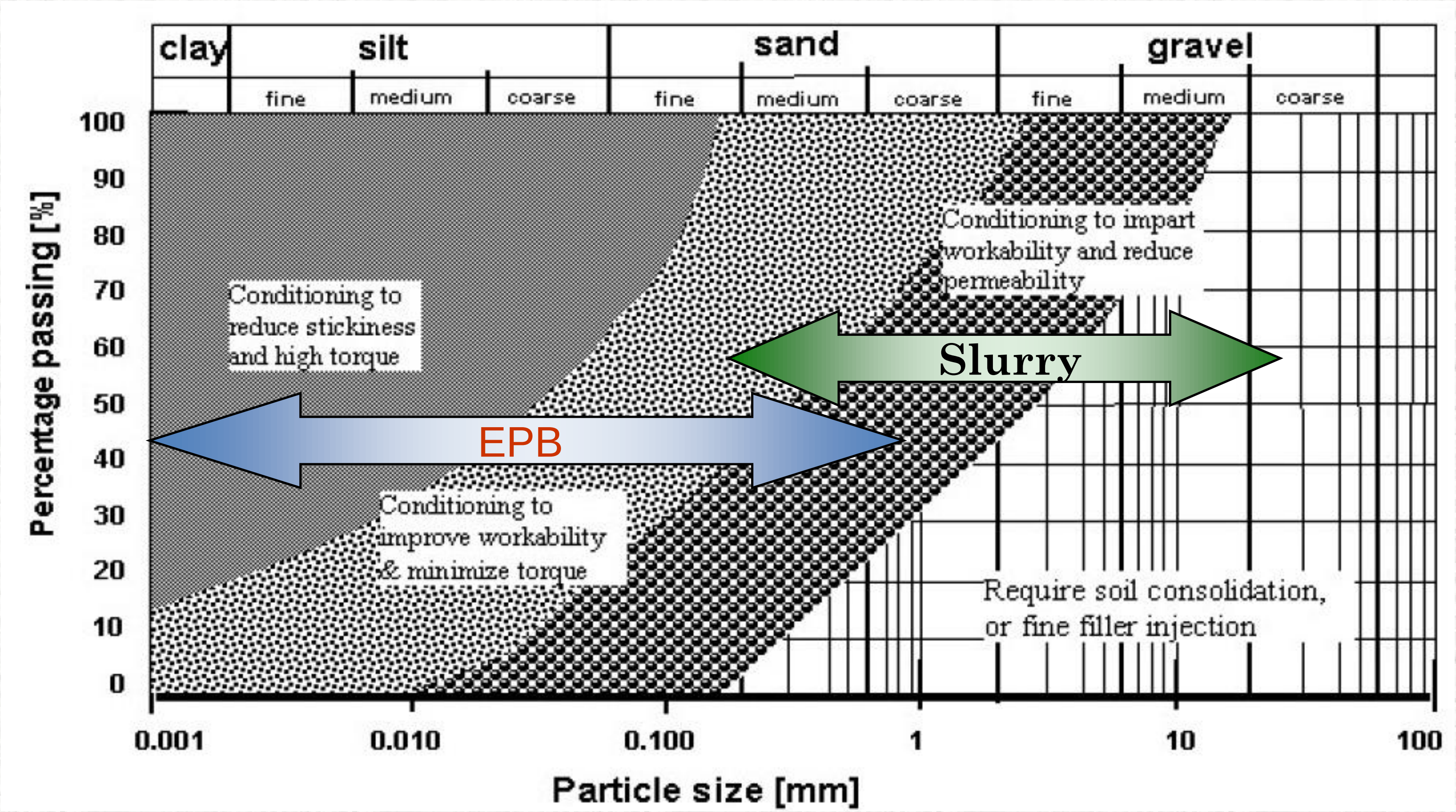


Closed Face Shield, Face Support

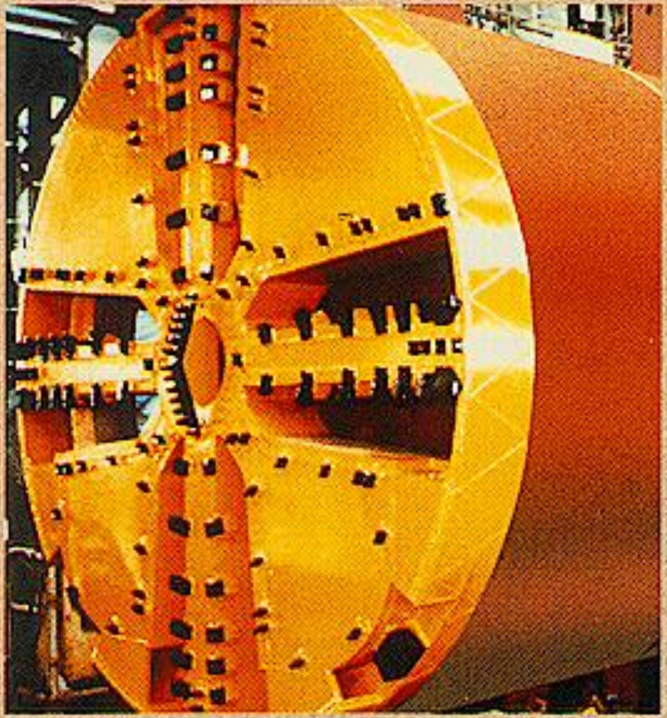


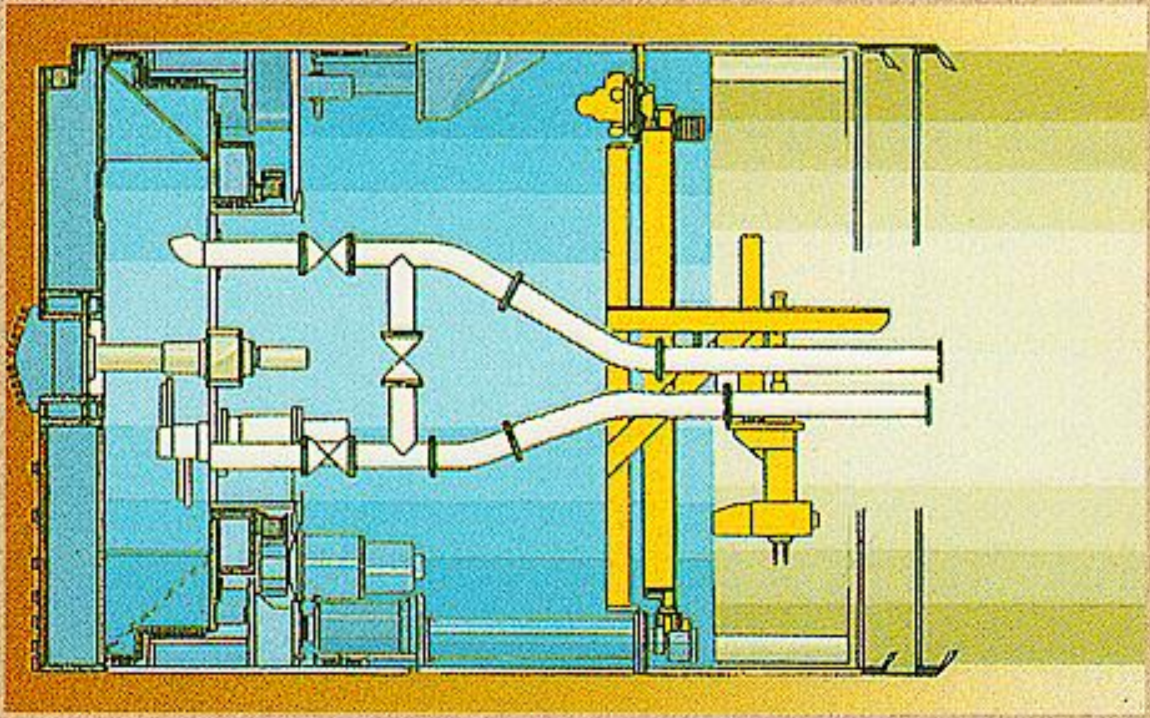
Closed Face Shield Selection

Function of Soil Type



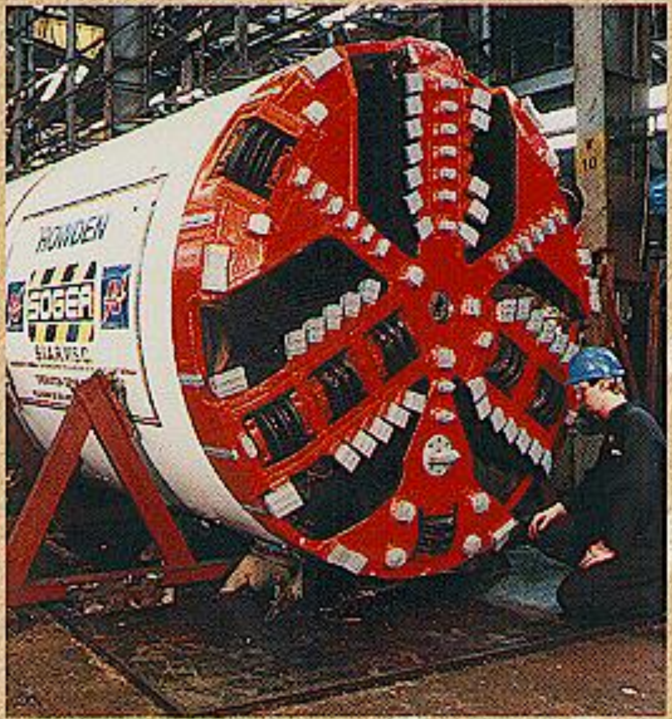
Slurry TBM

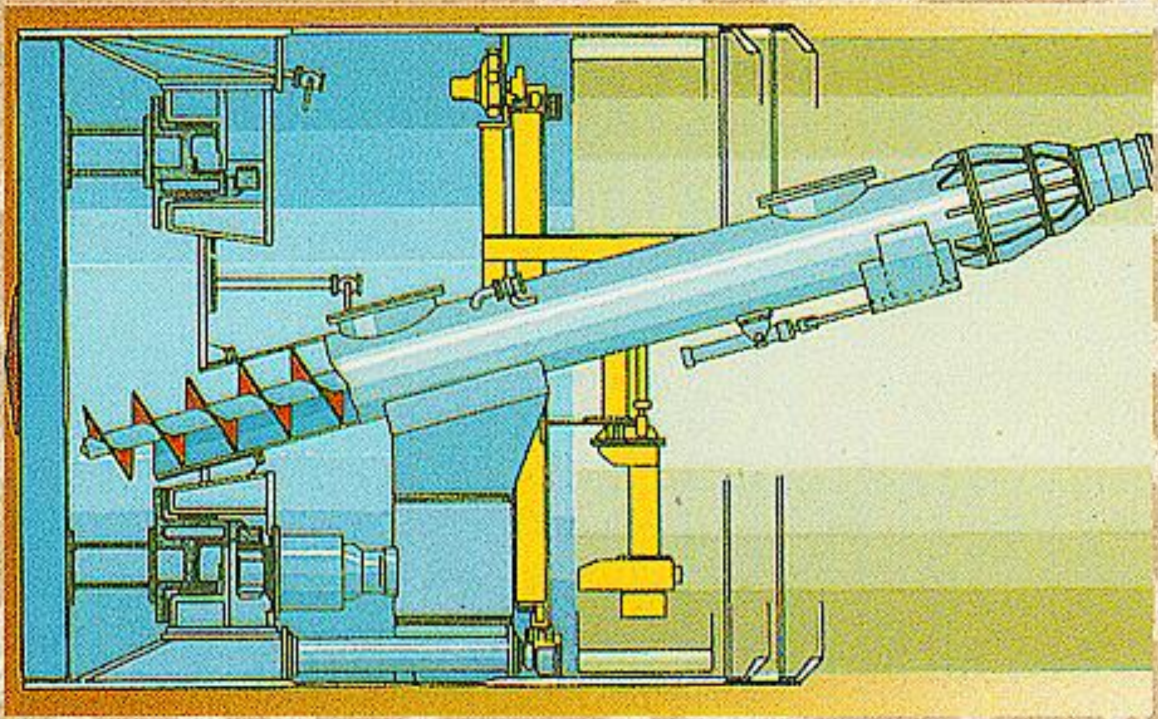




Slurry Machine

EPB Machine





Earth Pressure Balance Machine

Case Histories

Sequential Excavation Method (SEM)

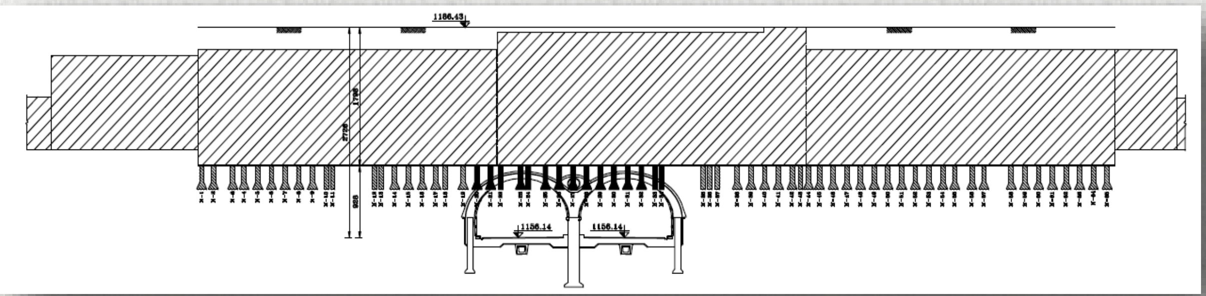
Challenges

- Crossing of Metro line and station, within 3 ft of the crown
- Close proximity to buildings and active traffic above
- Small footprint for shafts and portals
- Highly variable ground with cobles and boulders
- Shallow depth and changing slopes
- Existence of ancient water conduits (Qanats) and possibility of flash floods at the face
- Leaky old water lines along the tunnel

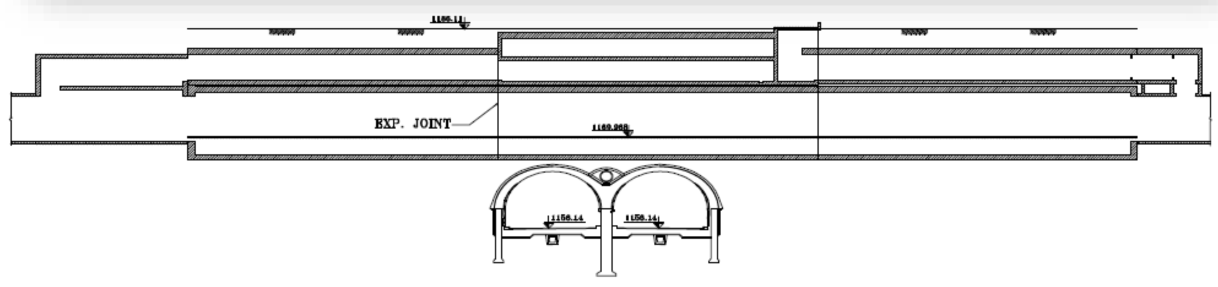
Crossing of Subway Station

Intersecting Station in

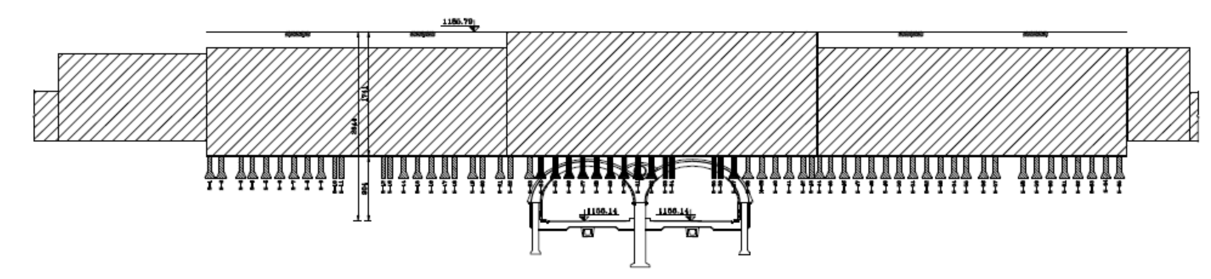
- North



- Middle

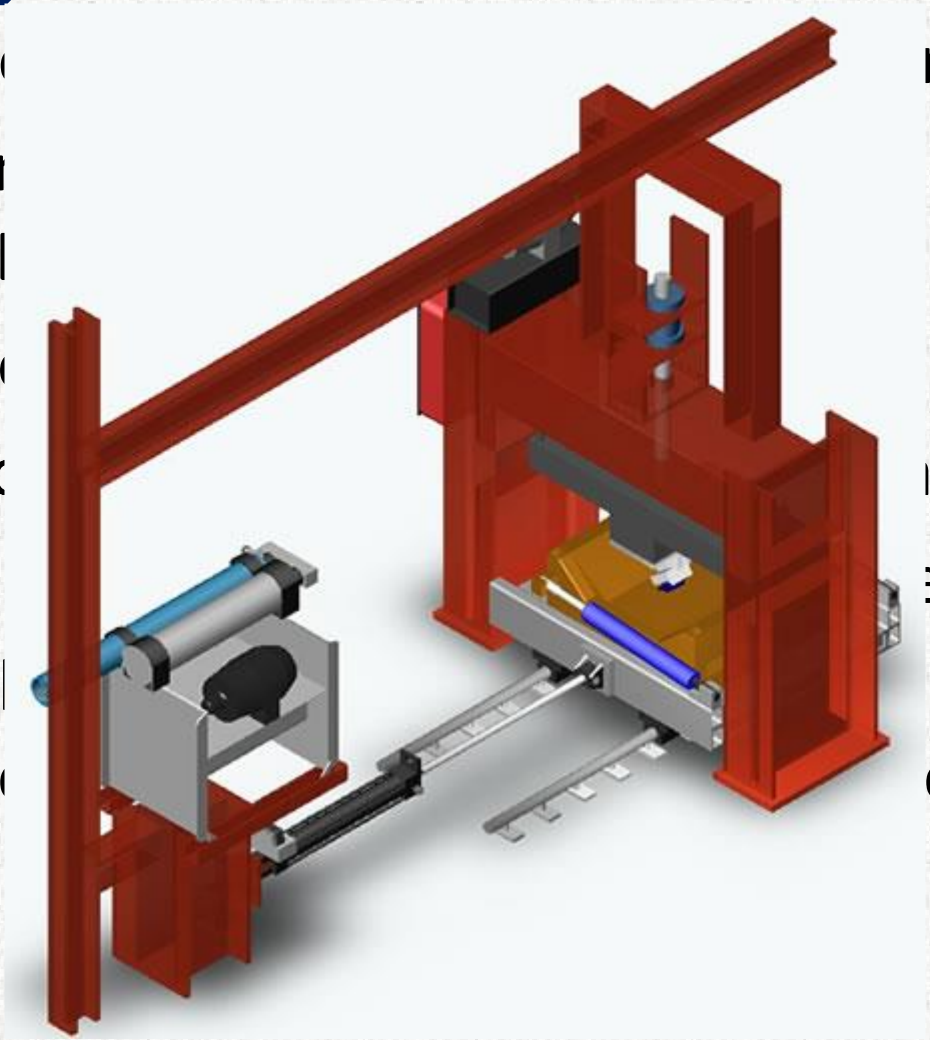


- South



Twin Peaks Tunnel, Colorado Spring, CO

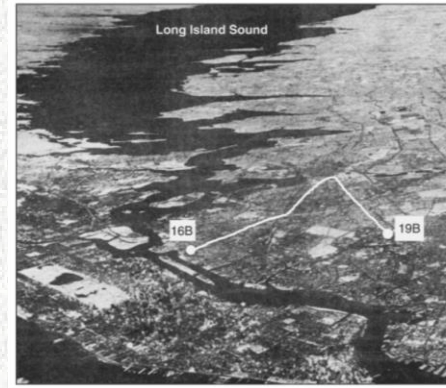
- C rrison Knudsen
- S nel constructed by Tl
- R
- L te
- H e
- C s (DSC) for rock b eotec.



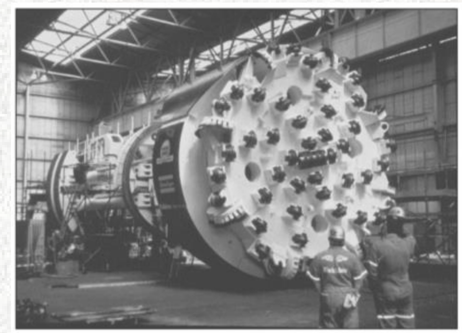
Boston Outfall Tunnel

- 10 mile of 26.5 ft diameter tunnel, lined with segmental lining
- Double Shield TBM was used by Kiewit-Atkinson-Kenny JV
- Geology, mainly argillite, at depth of ~200 ft under the Atlantic Ocean, staring from a shaft in Deer Island
- DSC claim for penetration (got 9 ft/hr instead of expected 15 fr/hr), low penetration attributed to rock anisotropy
- DSC for excessive grouting

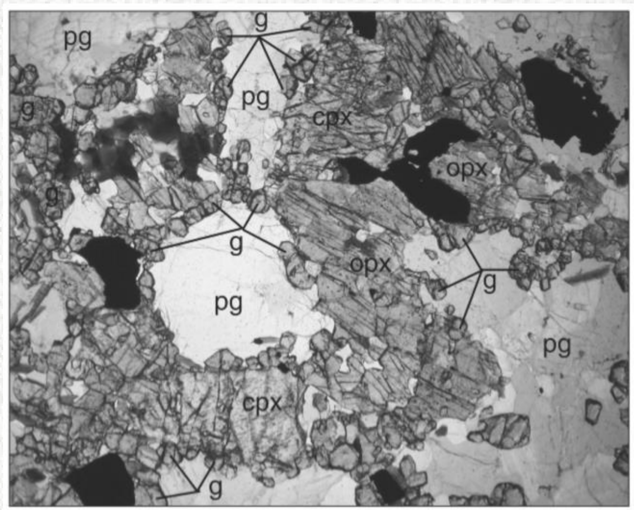
Queens Tunnel, New York City

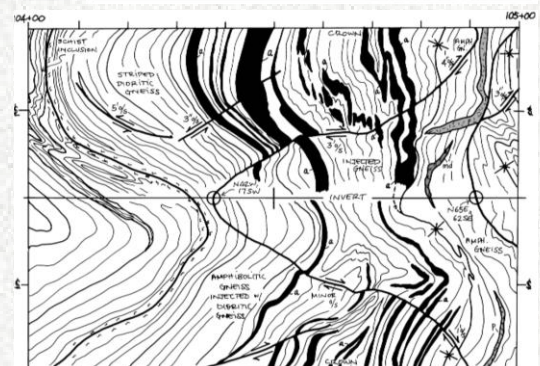


- 5 mile long, 23′ 2′ wide, and ~700′ deep tunnel through igneous/granitic rock.
- Contactor was Kiewiet-Shea
- Low penetration rates claim (~6′/hr [actual] vs. ~9′/hr [anticipated]) attributed to changed rock mass conditions, high-grade metamorphism of the rocks
- In other words, harder than expected rock but broken ground with frequent shear zones.



- Earlier tunnel in Queens by Shiavone – Shea had a claim for excessive cutter cost

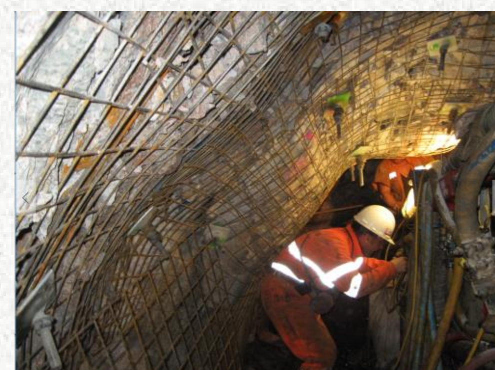




Merguerian, Charles (primary); Ozdemir, Levent
RETC-2003

Symour Capilano Twin Tunnels in Vancouver, BC

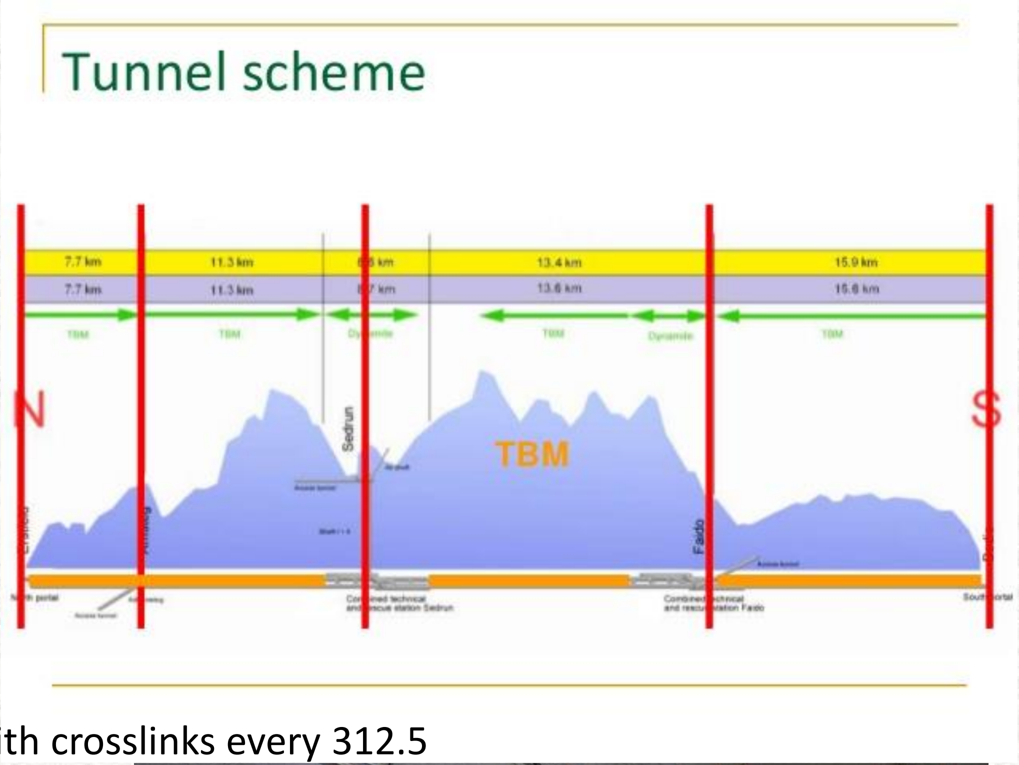
- Twin tunnel for Raw and Treated Water from the dam to treatment plant and back
- 7 km each, 3.8 m (~13ft) dia. ~300-600 m deep
- Mainly granite and igneous rocks, some areas with weathered granite
- Spalling and rock falls due to stress concentrations at 5 & 11 O'clock position
- High in situ horizontal stresses of about 2-3.5 time vertical/gravitational stress
- Work was interrupted by rock burst!
- 1st Contractor stopped due to safety concerns and was terminated,
- 2nd contactor completed the job.
- Over ~$100 in Claims



Source: Tunnel Talk

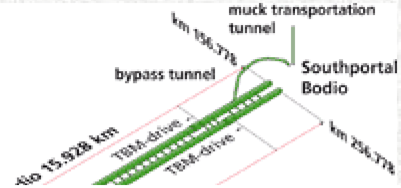
The St Gotthard Base Tunnel in the Alps

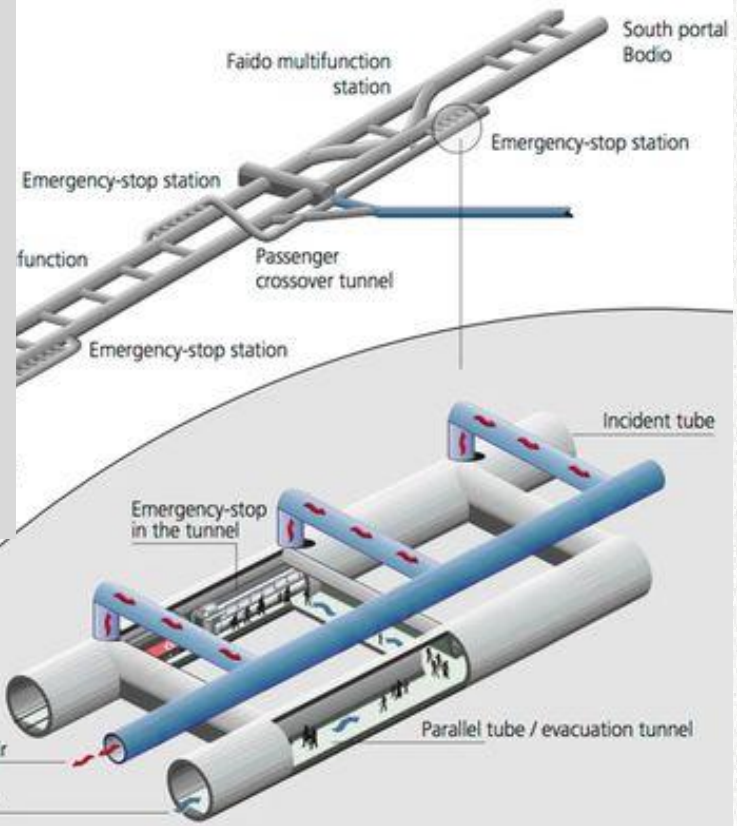
- Total Tunnel Length
  - Nominal length 57.1 km
  - System length 151.8 km
  - TBM 98.1 km
  - Conventional 53.7 km
- Boring diameter
  - 8.8 / 9.4 / 9.5 / 11
- Overburden(min-max)
  - 100 – 2’350 m
- Characterization scheme
  - 2 single track tubes, connected with crosslinks every 312.5
  - 2 multifunction stations
  - 3 access galleries
  - 2 vertical shafts (800 m)
  - 1 bypass gallery
  - 1 inclined ventilation shaft

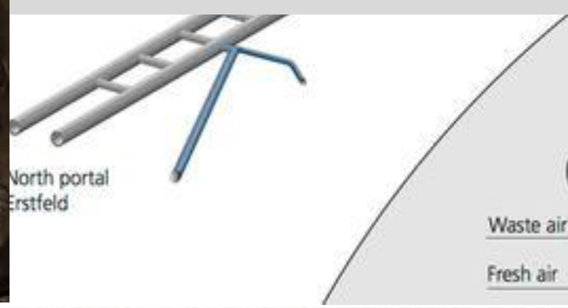


The St Gotthard Base Tunnel in the Alps

- Main issue in this project was the In-situ stress and ground sqeezing
- Designed for up to 3 ft (~1m) of ground convergence
- Open type TBMs used for excavation, this allowed for convergence without entrapment of the shielded machines



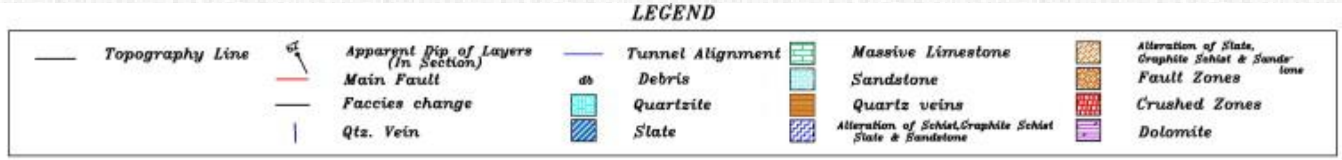


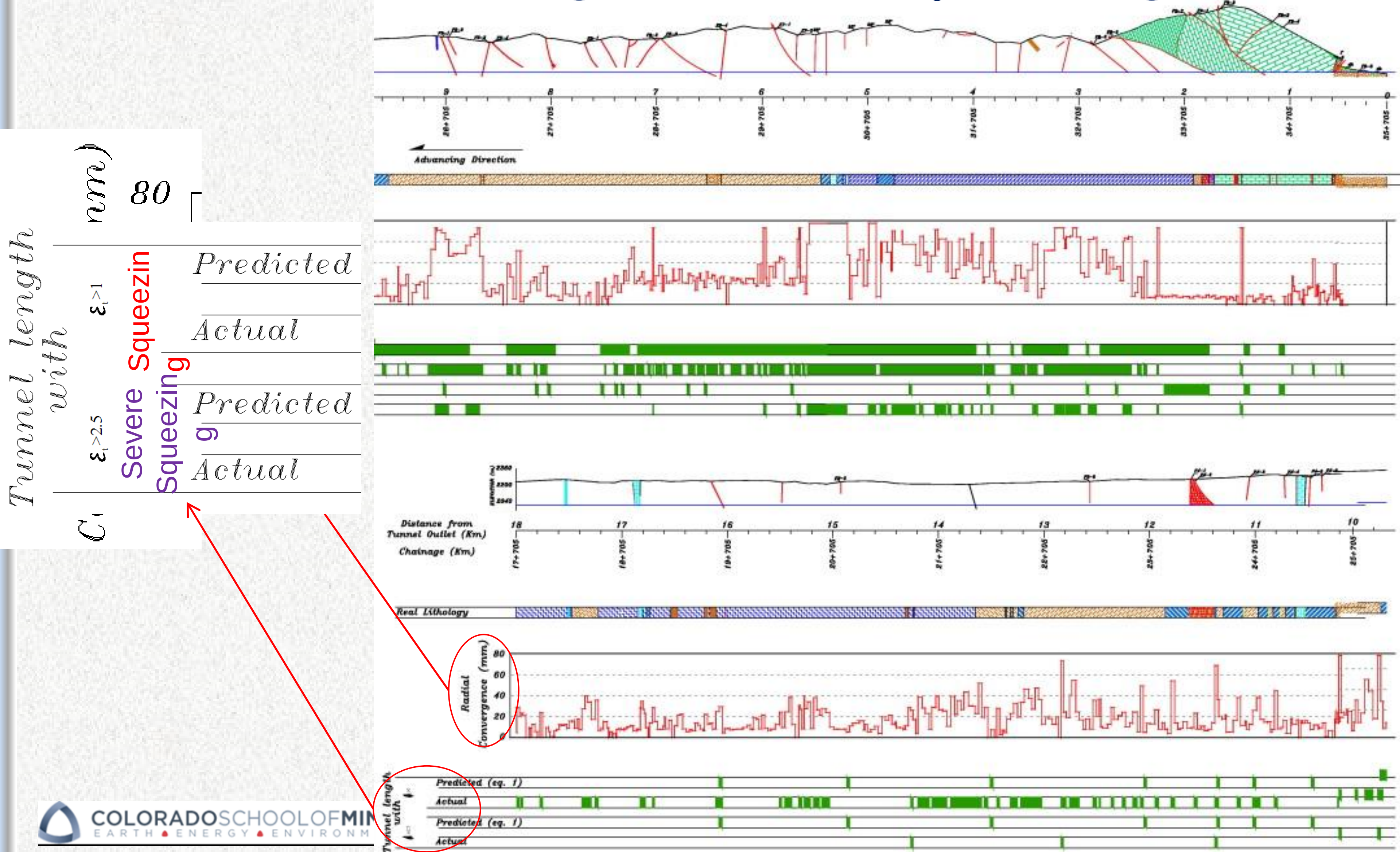


GHOMRUD PROJECT, IRAN

- Overall Tunnel length: >50 km
- Broken into lots I-IV 9 km each + 14 km in lot #V
- Lots IV, III, and part of II excavated by Double Shield TBM for the length of 24+450 m
- TBM manufacturer: WIRTH Co.
- Diameter: 4.5 m (OD) 3.8 m (ID)
- Support: Hexagonal Segmental lining
- Start of excavation: Spring 2004
- End of excavation: Spring 2009

Convergence & TBM jamming





TBM Jamming due to Squeezing

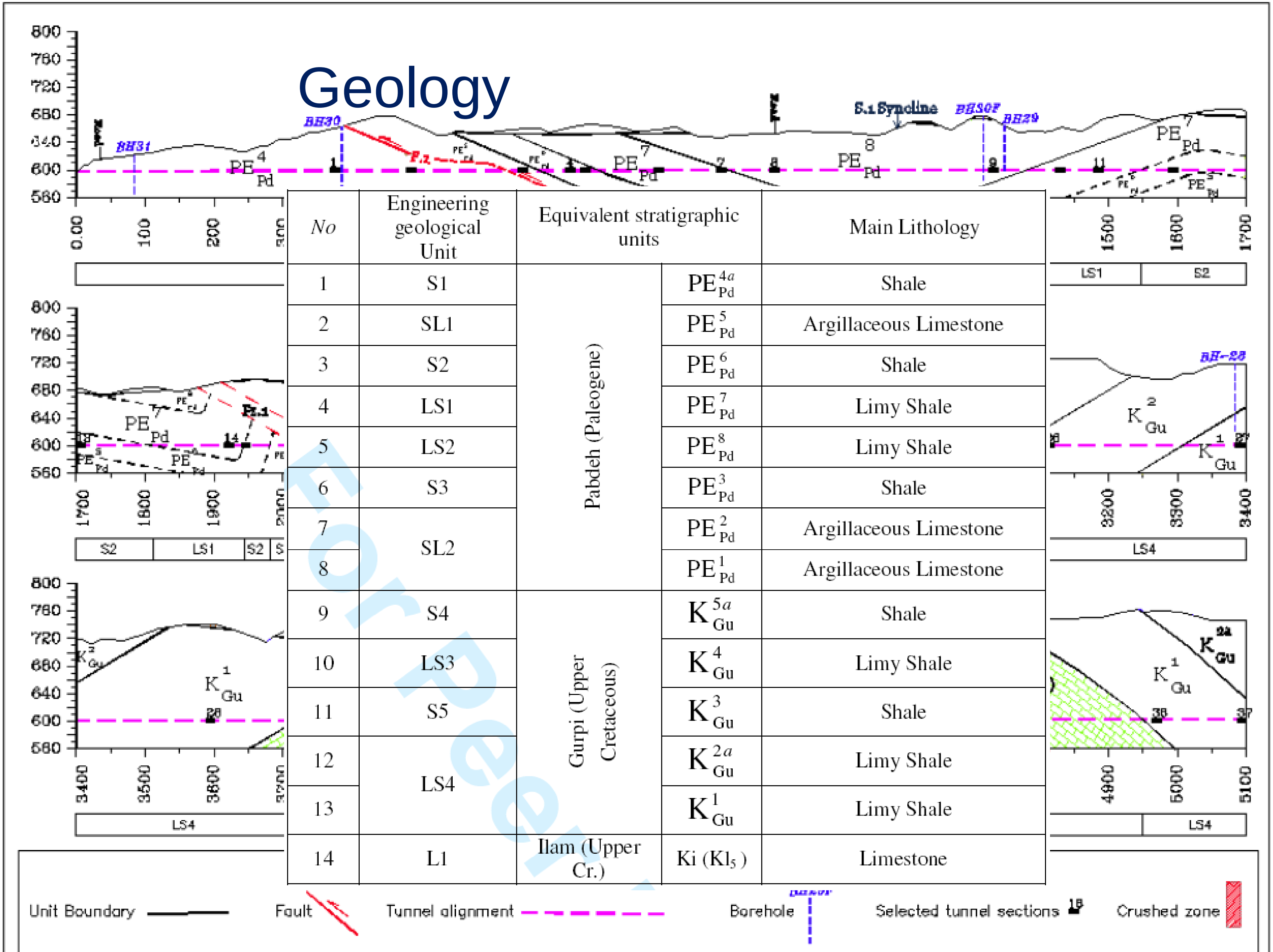
,525 mm
,495 mm
65 mm
35 mm
,460 mm
,380 mm
145 mm

Zagros long tunnel

- The Zagros tunnel is the largest water transfer project in western Iran situated within the Zagros mountain range
- The second lot of tunnel is approximately 26 km long and 6.73 m in diameter, currently under construction using a double shield (DS) TBM
- The tunnel passes through a variety of sedimentary rock formations with frequent changes in rock mass qualities from poor to very good
- The machine encountered many adverse geologic conditions, all of which resulted in reduced TBM utilization

Machine diameter	6,730 mm
Number of cutters	42
Cutter diameter	432 mm (17”)
Average cutter spacing	90 mm
Cutterhead torque	4,747 kNm
Thrust force	29,038 kN
Rotational speed	0-9 rpm

Geology

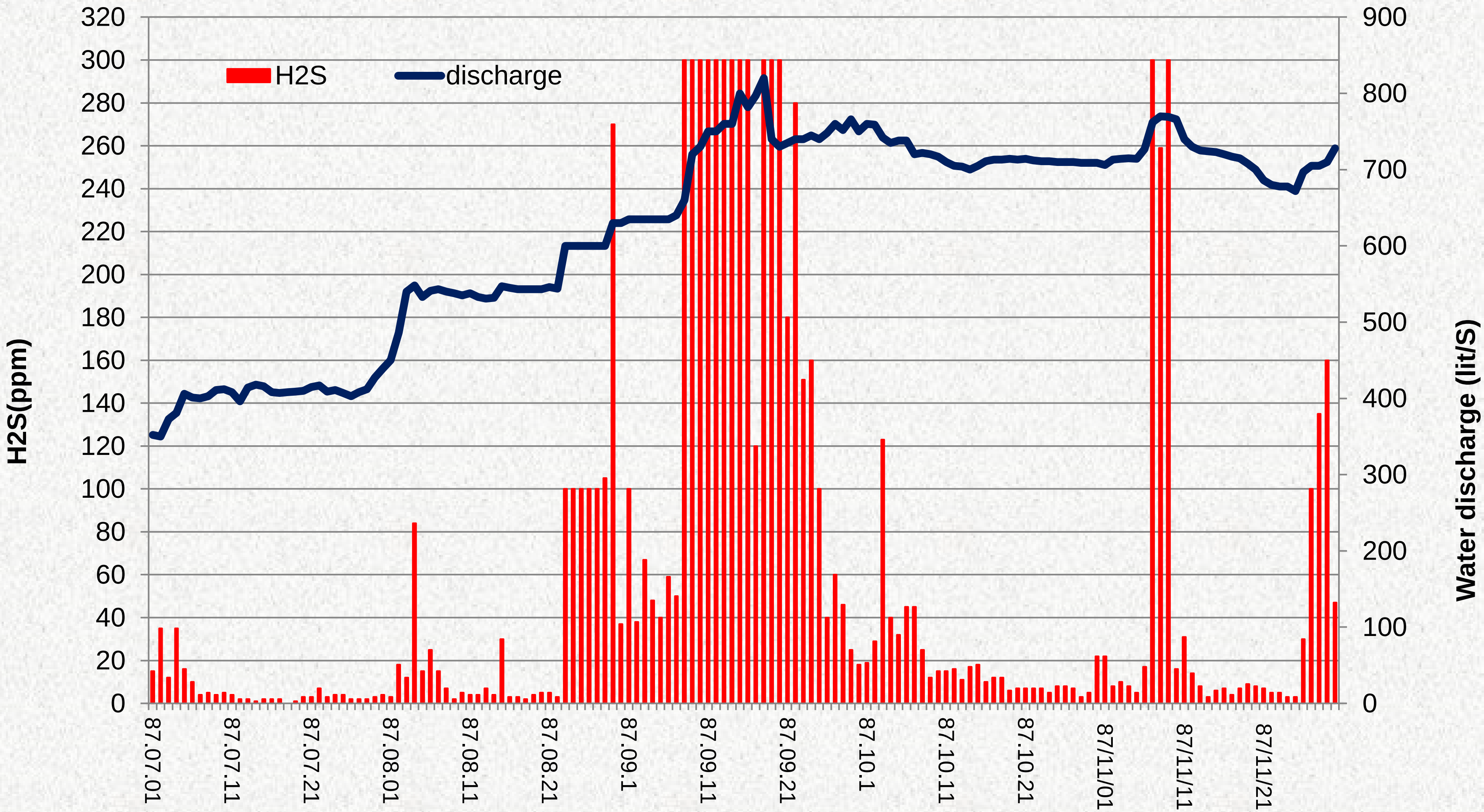


No	Engineering geological Unit	Equivalent stratigraphic units		Main Lithology
1	S1	Pabdeh (Paleogene)	PE^{4a}_{Pd}	Shale
2	SL1		PE^{5}_{Pd}	Argillaceous Limestone
3	S2		PE^{6}_{Pd}	Shale
4	LS1		PE^{7}_{Pd}	Limy Shale
5	LS2		PE^{8}_{Pd}	Limy Shale
6	S3		PE^{3}_{Pd}	Shale
7	SL2		PE^{2}_{Pd}	Argillaceous Limestone
8			PE^{1}_{Pd}	Argillaceous Limestone
9	S4	Gurpi (Upper Cretaceous)	K^{5a}_{Gu}	Shale
10	LS3		K^{4}_{Gu}	Limy Shale
11	S5		K^{3}_{Gu}	Shale
12	LS4		K^{2a}_{Gu}	Limy Shale
13			K^{1}_{Gu}	Limy Shale
14	L1	Ilam (Upper Cr.)	Ki (Kl_5)	Limestone

Gas emission incident in Zagros long tunnel

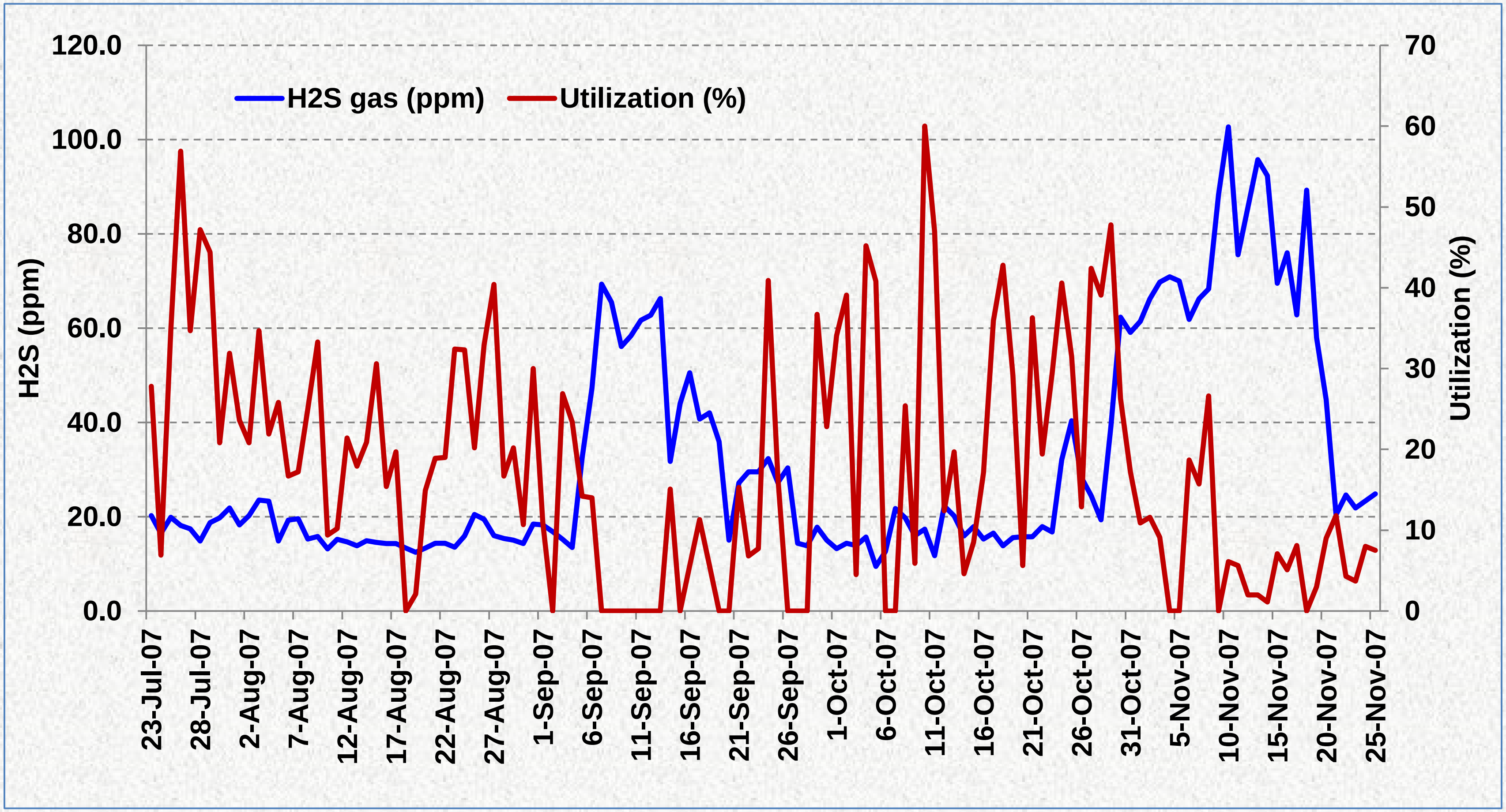
- The toxic hydrogen sulfide (H_2S) and explosive methane (CH_4) are the gases mainly encountered along the tunnel route
- The gas origin was existing sulfide minerals and in particular Pyrite and also natural gas and oil bearing formations along the tunnel alignment which are known as the typical host of oil reservoirs in western Iran
- Seepage of black tarry liquids into tunnel is an indicator of existing oil (gas)-bearing formations
- The gas is highly soluble in water and is often brought into the tunnel by seepage, where it is then released into the atmosphere

Gas emission incident in Zagros long tunnel



Gas concentration changes with water inflow rate

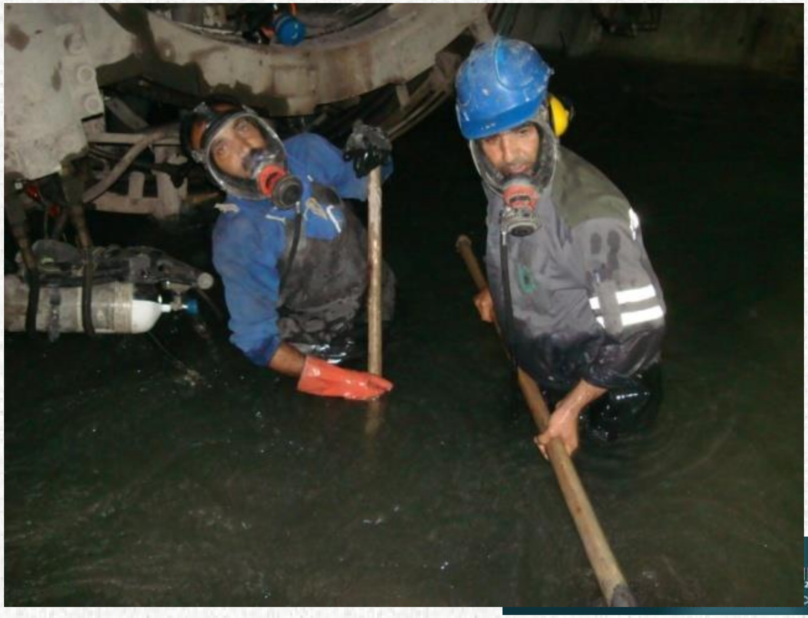
Difficult ground conditions and TBM utilization



Gas concentration vs TBM utilization

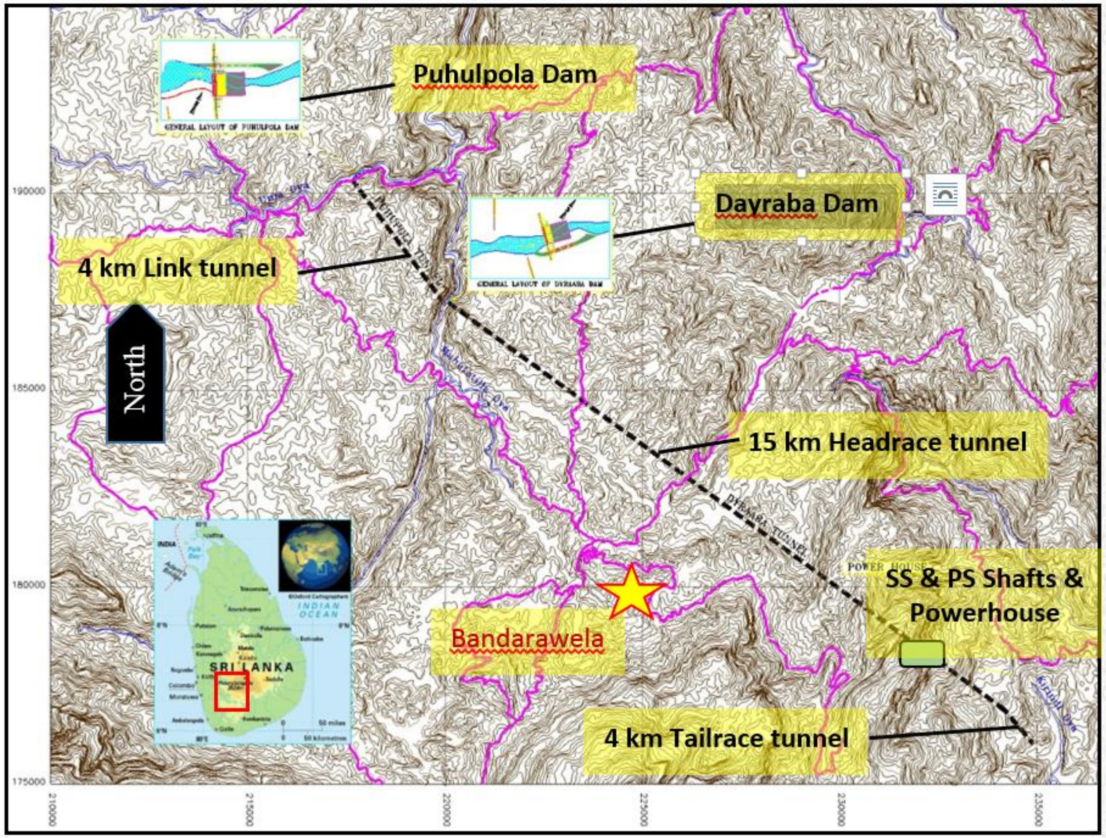
Gas emission related problems

- Health and Safety problems and hazards
- Difficult working conditions for tunnel crew
- 2 Fatalities due to negligence by the crew

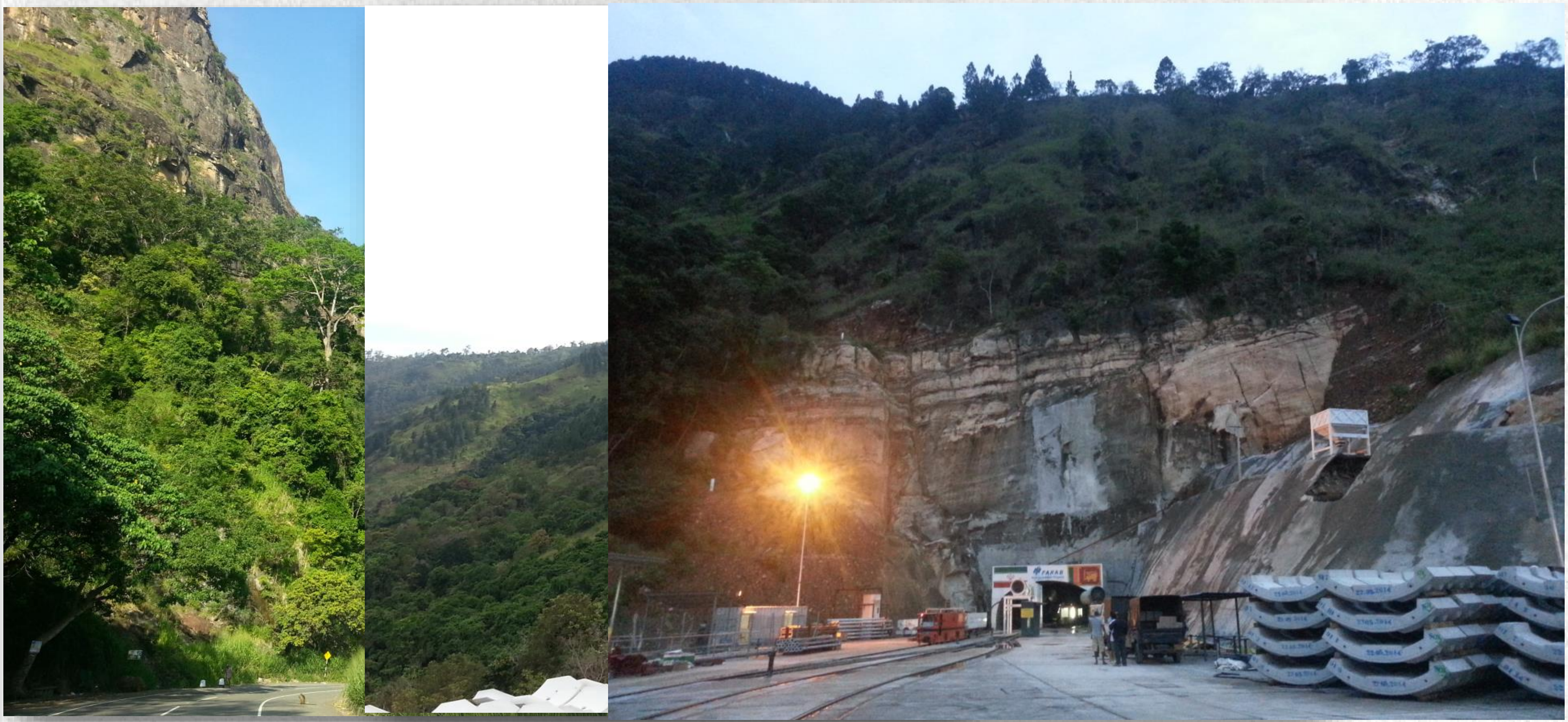


Oma-Uya Project, Sri Lanka

- Components:
  - 2 dams
  - 4 km transfer tunnel
  - 15 km Headrace Tunnel
  - Surge Shaft,
  - Drop Shaft
  - Powerhouse
  - Access tunnels
  - 4 km Tailrace tunnel
  - Misc. Access or maintenance facilities



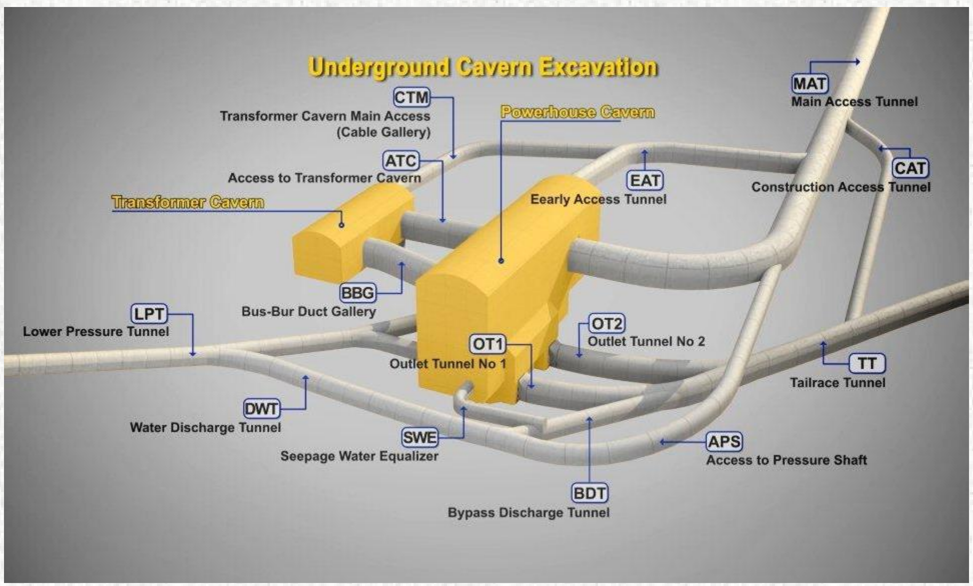
Uma Oya Multipurpose Project



Powerhouse

- Underground Powerhouse/Transformer
- Excavation Finished:

January 4th, 2016



Headrace Tunnel - Outlet

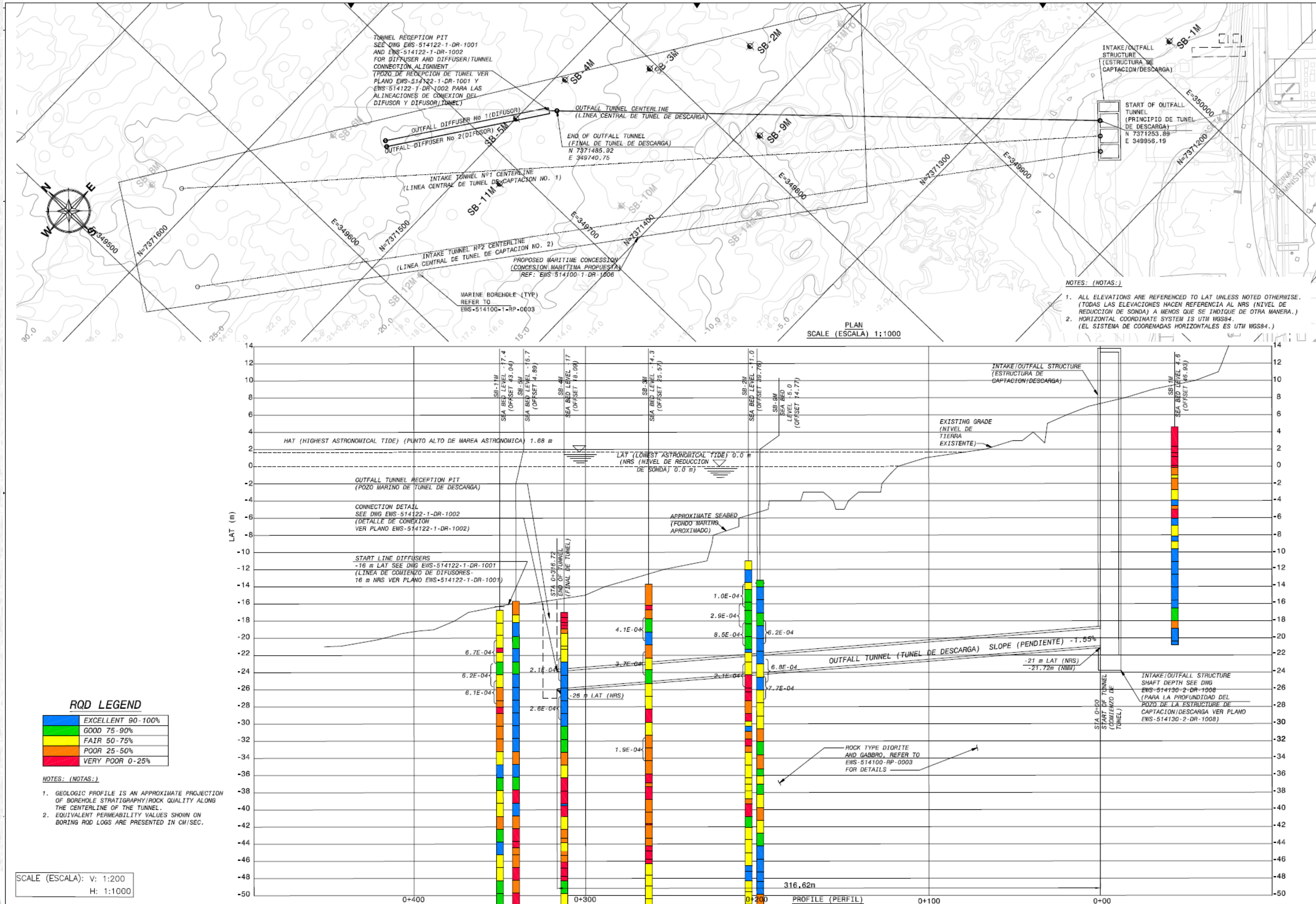
Headrace Tunnel

- Disc cutter wear in hard abrasive rocks

Headrace Tunnel,

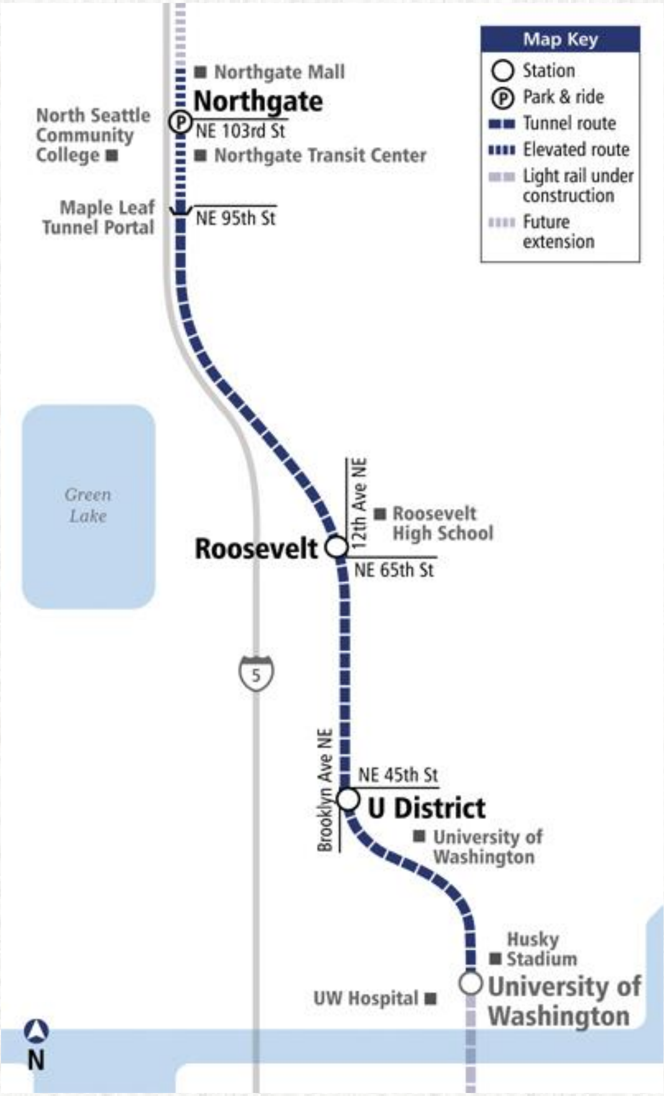
- Flooding and Water Issues

Escandida Project, Chile



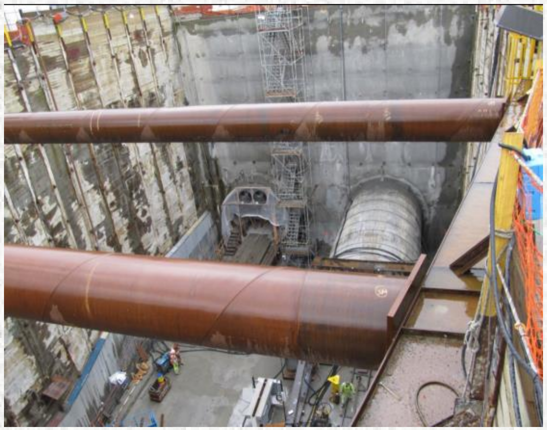
Seattle, Northgate tunnel project

- Typical Subway tunnel, ~20 ft Dia (6.3m), twin bore, in soft ground,
- 4.2-mile extension adds to the recently completed University Link tunnels running 3.2 miles
- Geology: various soils, sand, silty sand, clay. . . Under groundwater table, → pressurized face
- Two machines, one by Robbins one by Hitachi Zosen
- Tunnels are completed,
- Wear on the tools and cutterhead
- Issues with ground freezing for cross passages, and resulting heave

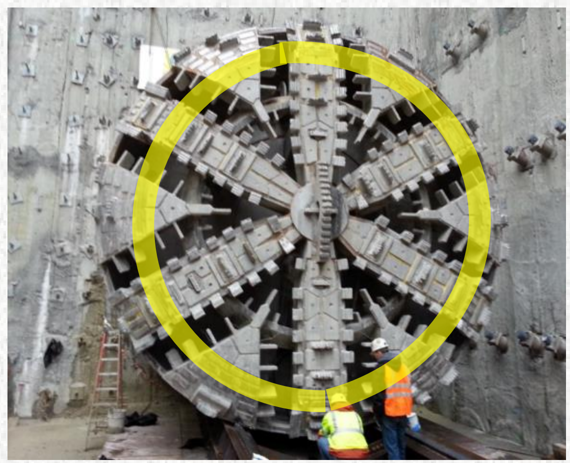


Seattle, Univesity Link and Northgate tunnel project

- Wear of cutterhead and tools due to soil abrasivity and Boulders





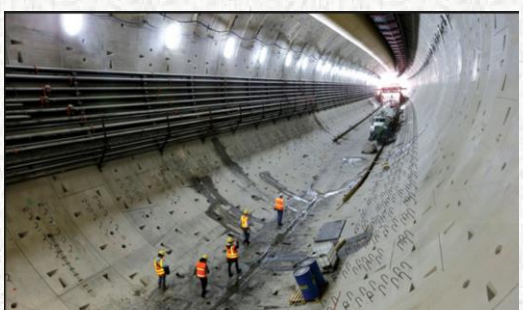


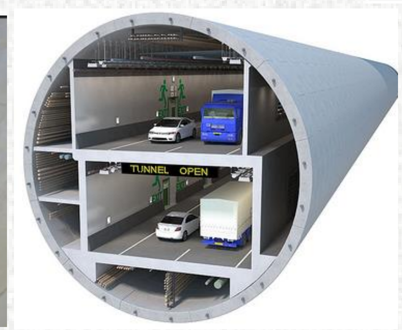

Seattle, SR-99 Alaskan Way Viaduct Replacement

- Twin-deck highway with a world record-breaking 17.4-m (57.3-ft) bored tunnel, Nearly 3.2 km (2 miles)
- Largest EPB machine in the world
- Tunnel is lined with segmental lining
- Geology: mainly sandy/silt soil/fill plus cobles & boulders, under water table
- Passing under the existing viaduct, high rises of downtown Seattle, close to Seattle fish market, aquarium, and the ferry terminal

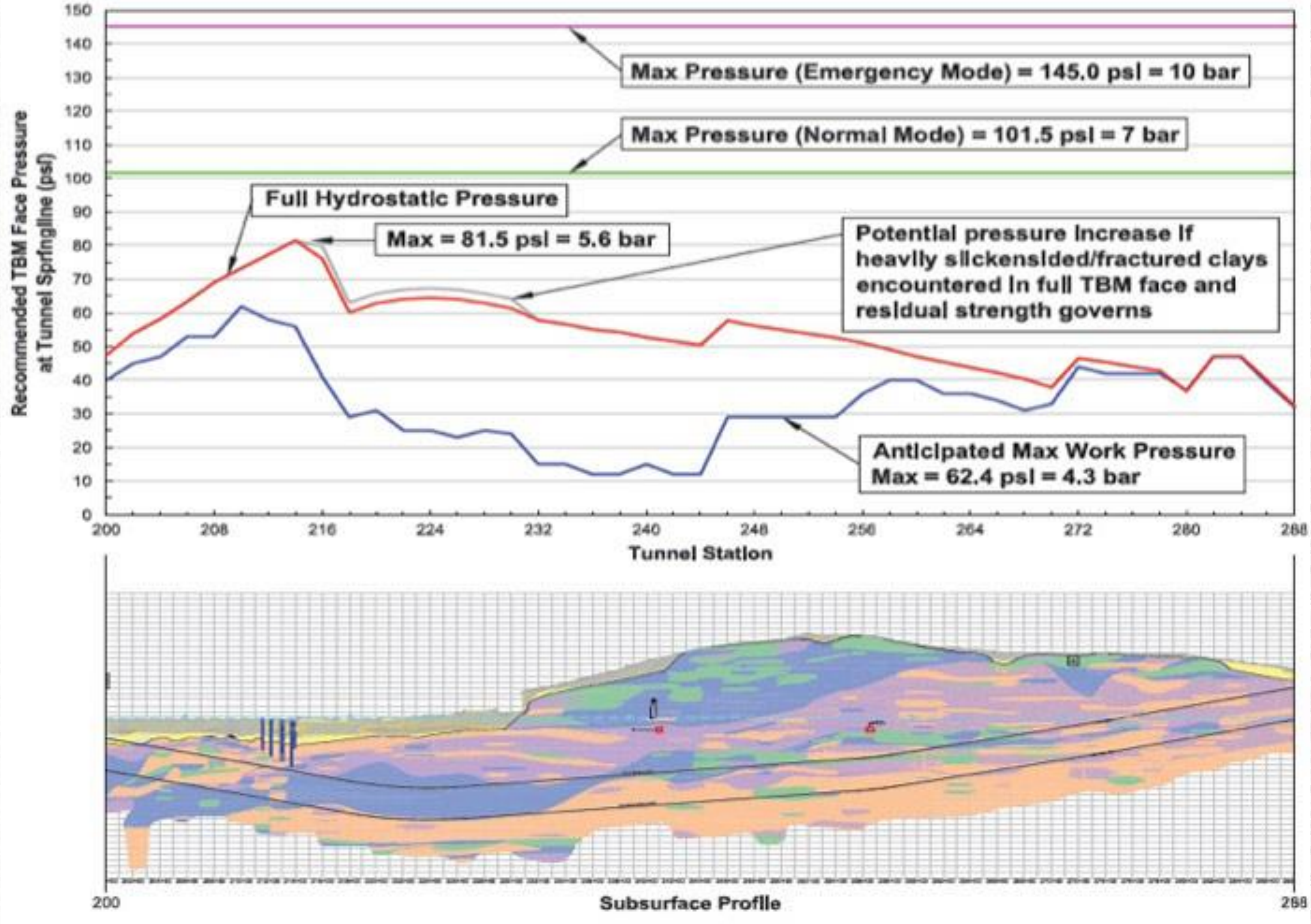
Table 1. EPBM specifications

Diameter	17.48m
TBM length + back-up	98.2m
TBM weight	6,664 tonne
Min horizontal radius	350m (1,150ft)
Min vertical radius	488m (1,600ft)
Max pressure in chamber	10 bar
Max thrust	392,000kN
Cutterhead displacement (forward)	400mm
Cutterhead power	24 x 560kW
No of disc cutters	122
No of replaceable knife bit cutters	255
No of thrust cylinders	28 x 2
Rotation speed	0-1.8 rev/min
Max torque at 0.88 rev/min	147,400kNm
Break-out torque	206,360kNm
Screw conveyor diameter/ type/length	1,500mm/ribbon/10.5m + 23.8m
Total power installed	22,861kW





Seattle, SR-99 Alaskan Way Viaduct Replacement



Source: TunnelTalk

Seattle, SR-99 Alaskan Way Viaduct Replacement

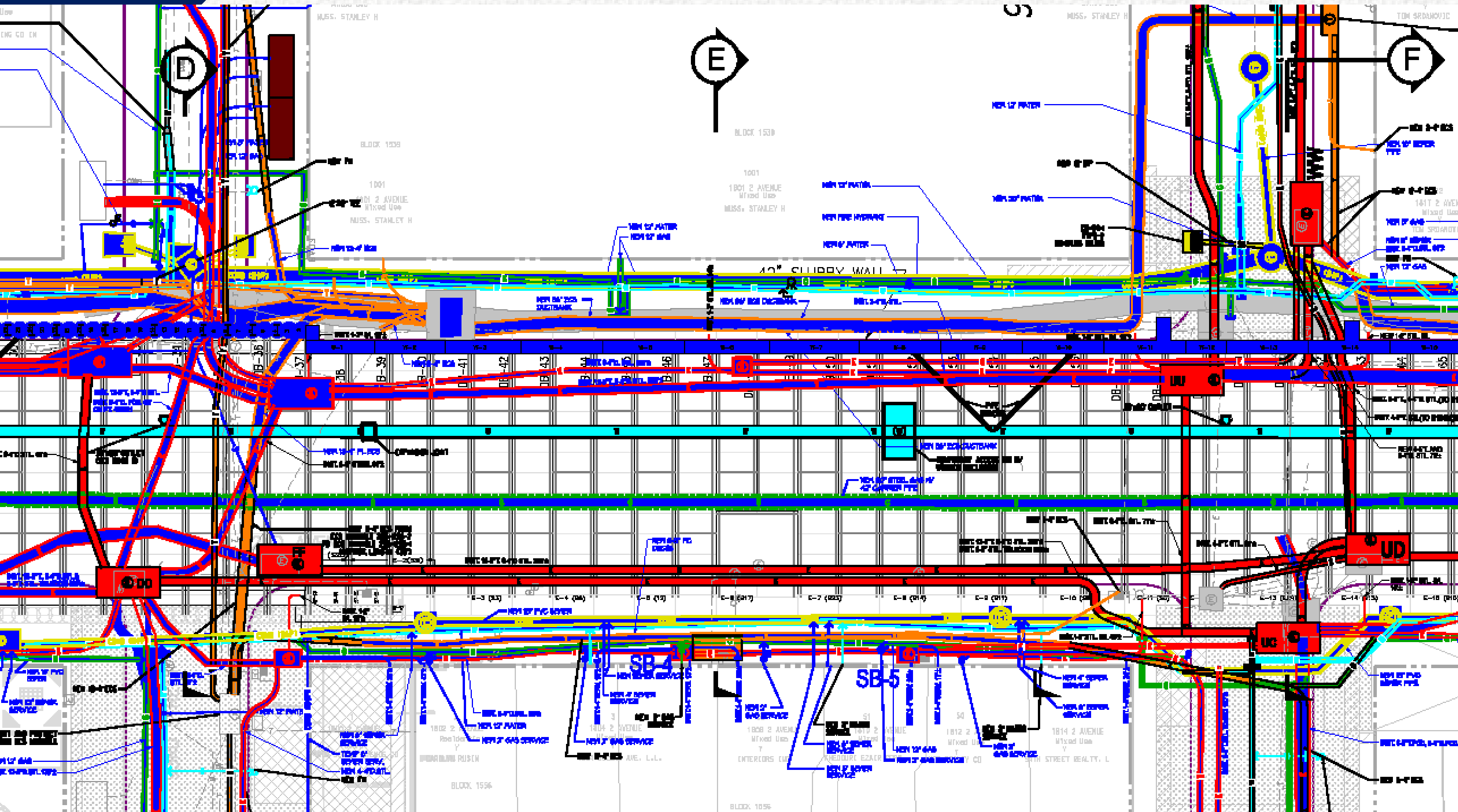
Site Investigation

CHALLENGES IN USE OF AVAILABLE SPACE

Laying a Water Main in Hampstead 1851

Underground New York City – turn of the century

Composite Utility Plan



Site Investigation

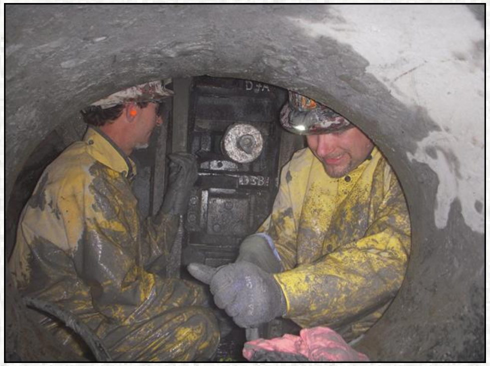
- Soil boring, delineation of soil/rock or Top of Rock interface
- Trenches, sampling shafts (for boulders), . . .
- Core logging
- Lab Tests
  - Soil, Rock, Groundwater
- In situ Testing
  - Groundwater table monitoring, Slug/Pump tests. ..
  - Borehole logging, Optical/Sonic televiewer
  - Dilatometer, Pressure meter tests
  - In-situ stress measurements

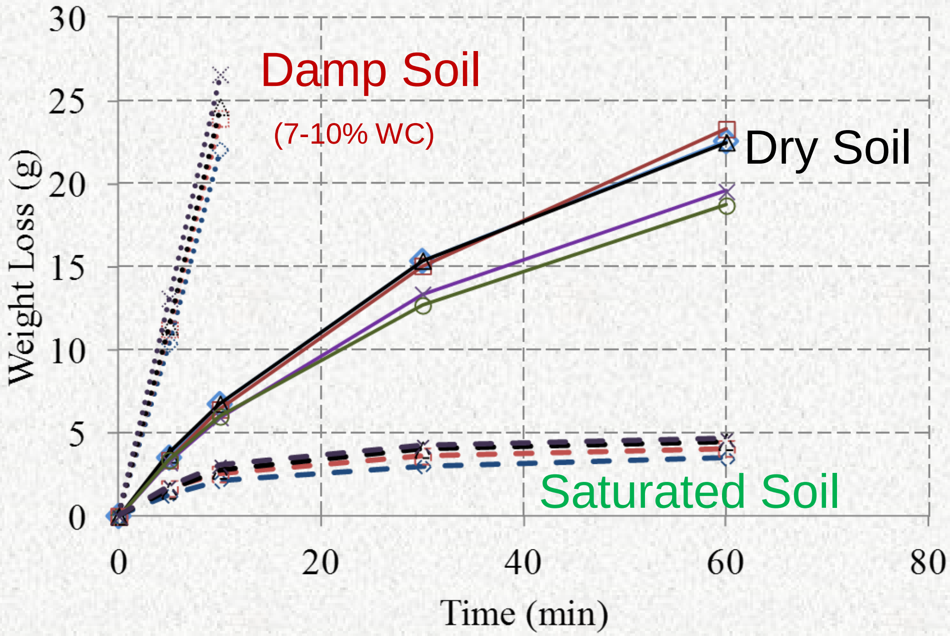
Laboratory Soil Testing

- Sieve
- Hydrometer
- Density /Specific Gravity
- Atterberg Limits
- Water Content
- Compaction
- PH measurement
- Permeability
- USCS
- Compressive Strength UU
- Compressive Strength CIU
- Organic Content
- Salinity
- Clay Minerals
- Shear Tests
- Soil Abrasion testing

Soil Abrasion

- Typically a non-issue in geotech investigation
- Very critical to tunneling due to implications of tool change under hyperbaric conditions, high cost, risk, and safety issues
- Relatively new, no standard testing, still under study.





Proposed Soil Abrasion Testing System

Rostami, J., Alavi Gharahbagh, E., Palomino, A.M., Mosleh, M., 2012. Development of Soil Abrasivity Testing for Soft Ground Tunneling Using Shield Machines, *Tunneling and Underground Space Technology Journal*, Volume 28, pp. 245-256.

- ➢A unique testing device was designed and built specifically for this study.
- ➢The proposed test device consists of a cylindrical chamber (14 in diameter and 18 in length, 350×450 mm) where the in-situ conditions of the soil can be simulated.

- ➢The whole assembly is mounted on a drill press with a 5 hp drive unit. The drill press allows for various rpm settings down to 60 rpm.
- ➢The chamber is constructed as a pressurized chamber having the capability of performing tests under ambient pressures of up to 10 bar.

- ➢The chamber dimensions were selected to allow for soils potentially containing large gravel size particles, to simulate the in-situ conditions of the soil as closely as possible and avoid altering grain size distribution as in some other tests

Proposed Soil Abrasion Testing Method

Rostami, J., Alavi Gharahbagh, E., Palomino, A.M., Mosleh, M., 2012. Development of Soil Abrasivity Testing for Soft Ground Tunneling Using Shield Machines, *Tunneling and Underground Space Technology Journal*, Volume 28, pp. 245-256.

to avoid severe wear on the blades and also allow for more accurate measurement of the weight loss on the tools, the blades are fitted with steel covers.

The propeller,
to create maxin
with the soil,
drive shaft and
cylindrical cham

The propeller has three blades with the radius of 150 mm.

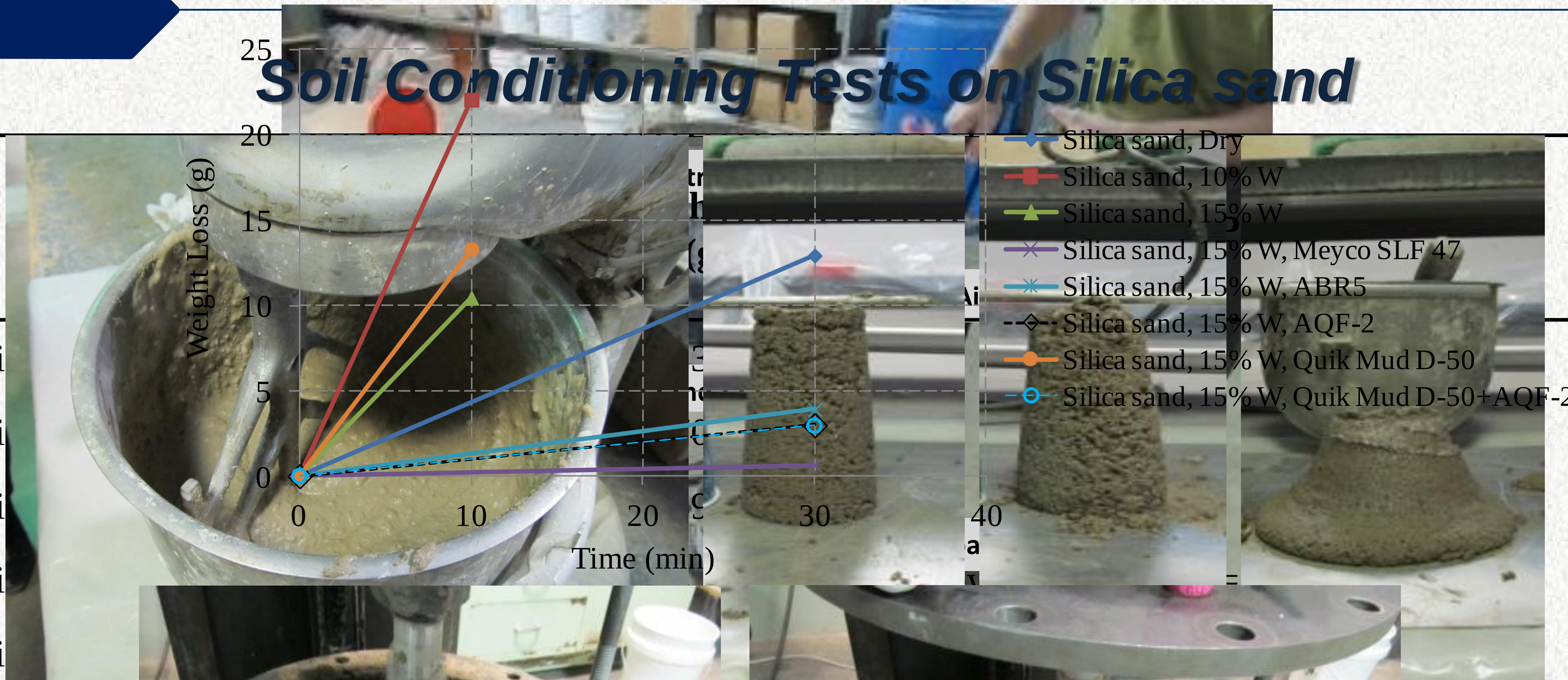
➢ **The covers weigh much less than the blades and can be easily removed and weighed using a high-precision scale and provide protection to the blade.**

This leaves an annular space of about 12 mm between the edge of the propeller blades and the walls of the chamber that allows for limited material flow inside the chamber.

Study of the Effect of Soil Conditioning on Soil abrasion

Alavi Gharahbagh, E., Rostami, J., Talebi, K., Ibarra, J., 2013. Experimental and Practical Study of Impact of Soil Conditioning on Soil Abrasion and Cutter Wear of EPB TBMs, RETC Conference, June 23-26, Washington, DC.

Soil Conditioning Tests on Silica sand



Sili
Sili
Sili
Sili
Sili
Silica sand
Silica sand
Silica sand

15%
Conc.
and mixed
SLF 47
r and mixed
25%
%, FER=14
R=17

ABR5

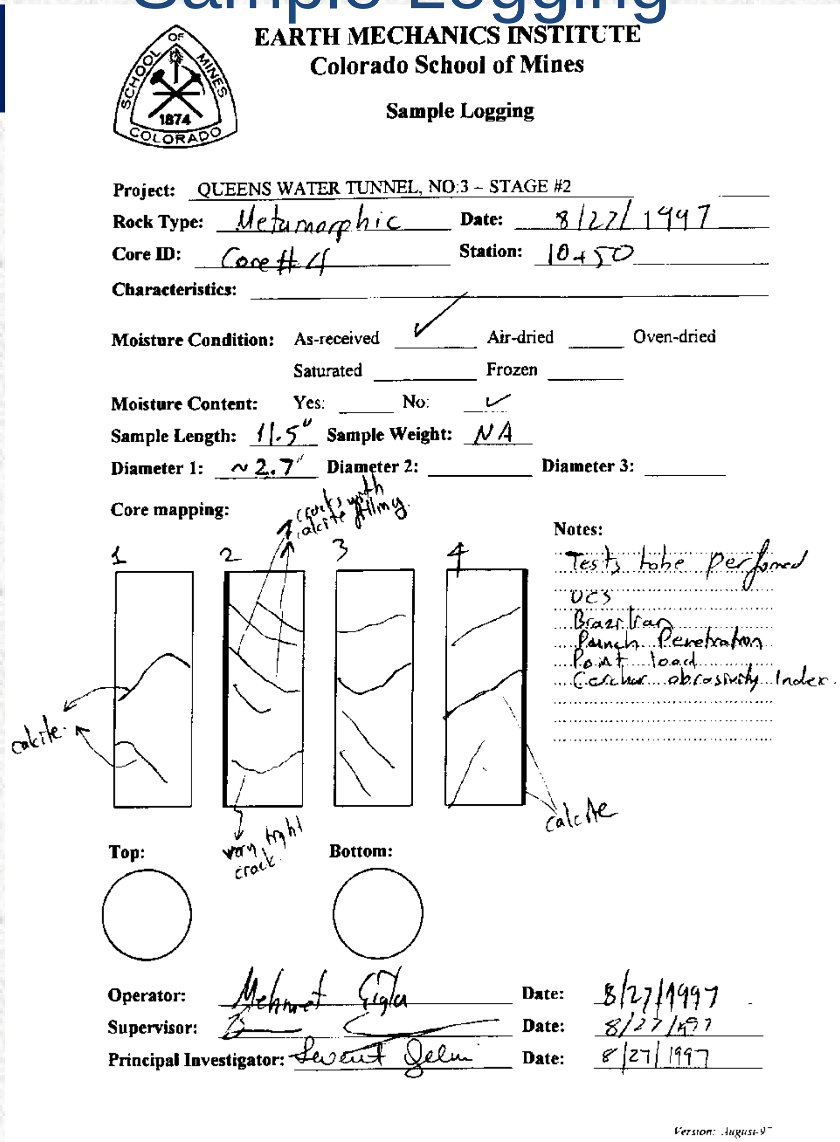
Meyco SLF 47

Soil conditioning tests on IDR sample

Physical Property Testing for Rocks

- Uniaxial Compressive Strength (UCS)
- Brazilian (Indirect) Tensile Strength (BTS)
- Cerchar Abrasivity Index (CAI)
- Punch Penetration Test
- Thin Section Petrographic Analysis
- Acoustic Velocities
- Point Load Index Test
- Triaxial Compression Test
- Static Elastic Modulus

Sample Logging



EARTH MECHANICS INSTITUTE
Colorado School of Mines

Sample Logging

Project: QUEENS WATER TUNNEL, NO:3 – STAGE #2

Rock Type: Metamorphic **Date:** 8/27/1997

Core ID: Core #4 **Station:** 10+50

Characteristics:

Moisture Condition: As-received ✓ Air-dried ____ Oven-dried

Saturated ____ Frozen ____

Moisture Content: Yes: ____ No: ✓

Sample Length: 11.5" **Sample Weight:** NA

Diameter 1: ~2.7" **Diameter 2:** ____ **Diameter 3:** ____

Core mapping:

1 2 3 4

cracks with calcite filling

calcite

very tight crack

calcite

Notes:

Tests to be performed

UCS

Brazilian

Punch Penetration

Point load

Cerchar abrasivity Index.

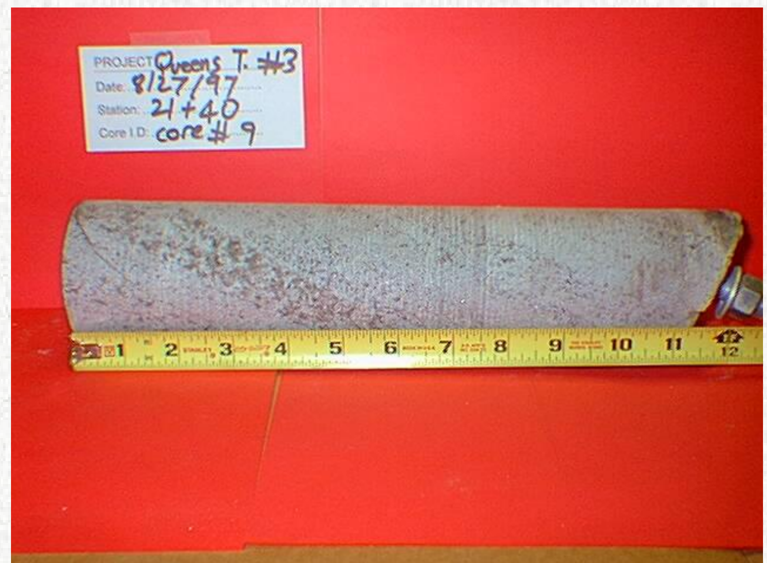
Top: **Bottom:**

Operator: Mehmet Cigla **Date:** 8/27/1997

Supervisor: **Date:** 8/27/1997

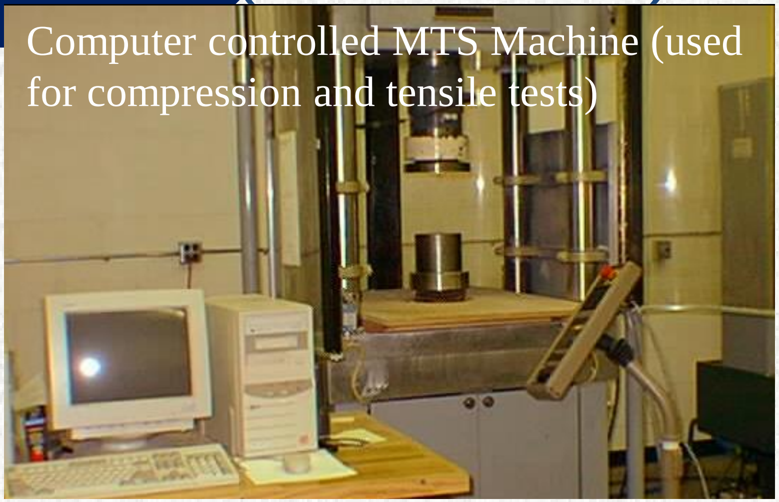
Principal Investigator: Levent Ozdemir **Date:** 8/27/1997

Version: August-97



Sample Preparation

Uniaxial Compressive Strength (ASTM 7012)



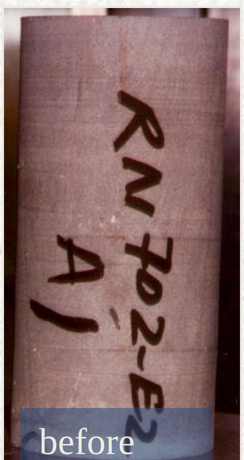
Computer controlled MTS Machine (used for compression and tensile tests)

$$\sigma_c = \frac{F}{A}$$

Where,

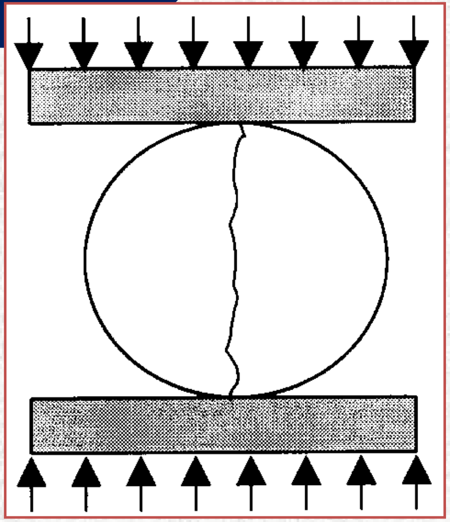
σ_c ➔ Compressive Strength of the Core Sample (MPa or psi)
F ➔ Applied Force at Failure (N or lb.)
A ➔ Initial Cross-sectional Area (mm^2 or in^2)

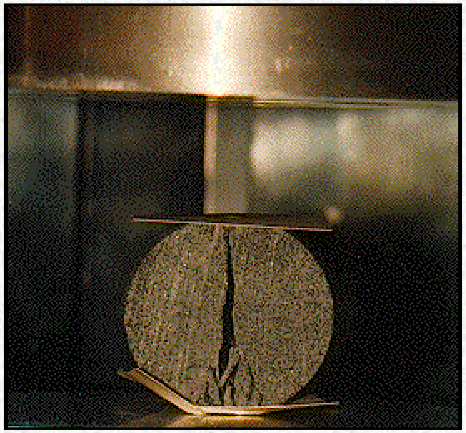
Non-structural Failure



Structural Failure

Brazilian Tensile Strength (ASTM D3967-95)



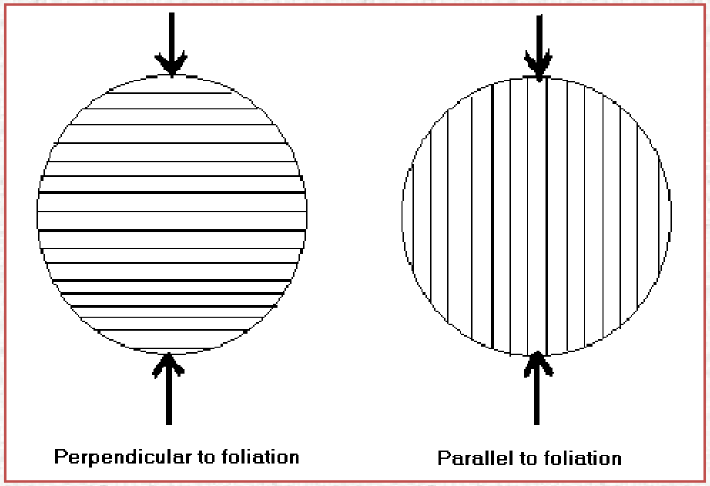


Normal Failure

Structural Failure

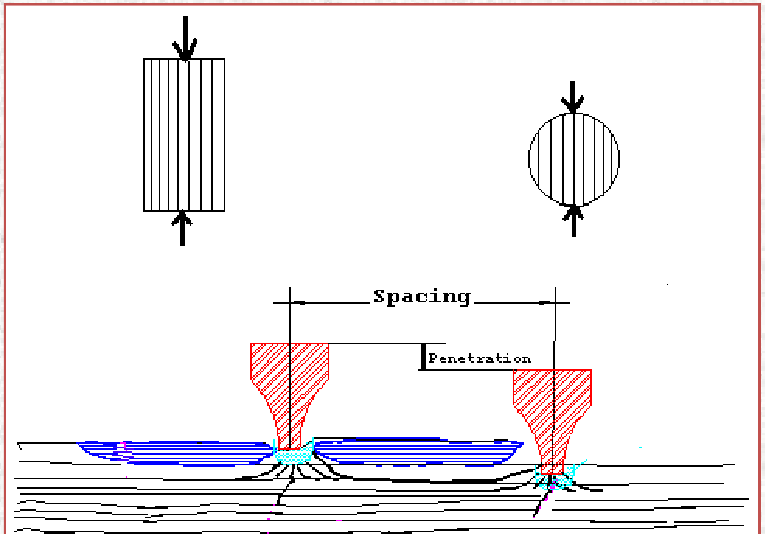
$$\sigma_T = \frac{2.F}{\pi.L.D}$$

σ_T ➔ Tensile Strength (psi)
F ➔ Failure Load (lbs.)
L ➔ Thickness of the disk (in.)
D ➔ Diameter of the disk (in.)

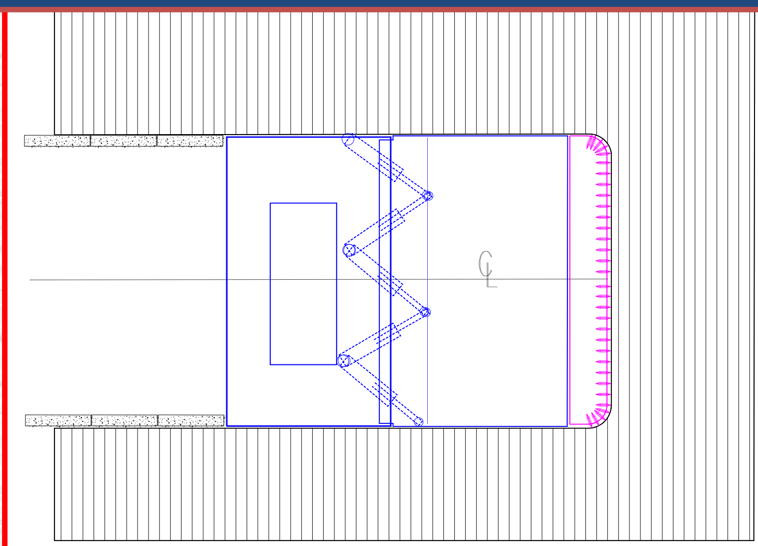


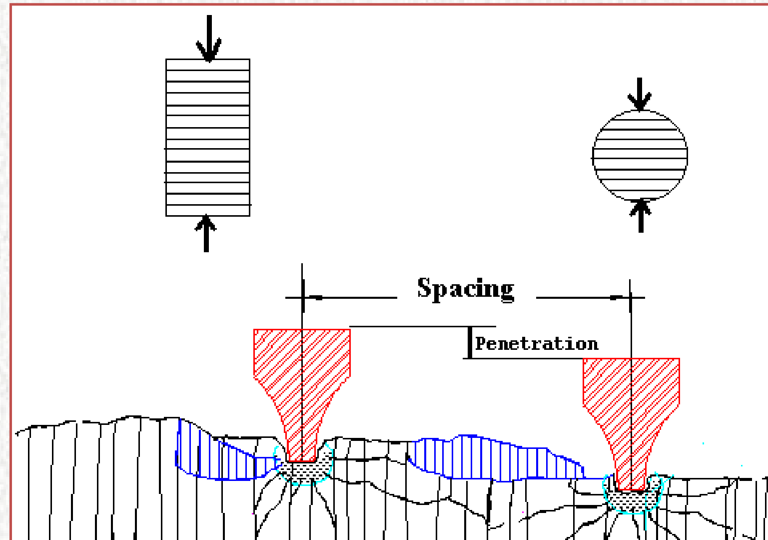
Effect of Foliation on Tensile Strength

Effect of Foliation/Bedding on Disc Cutting

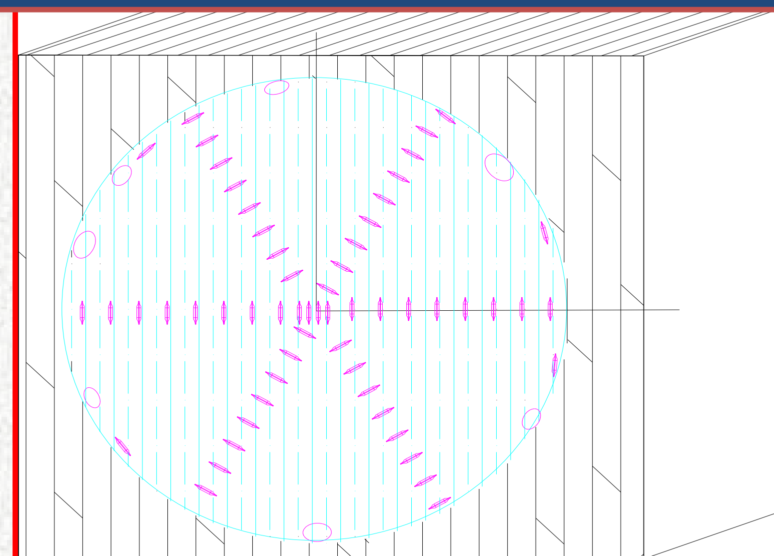


Tunneling perpendicular to foliation



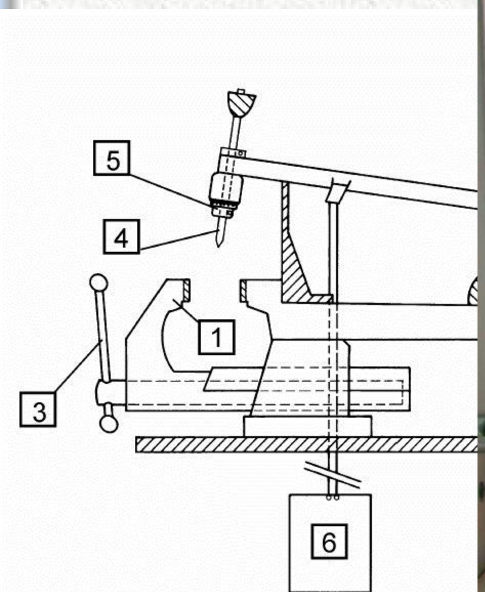


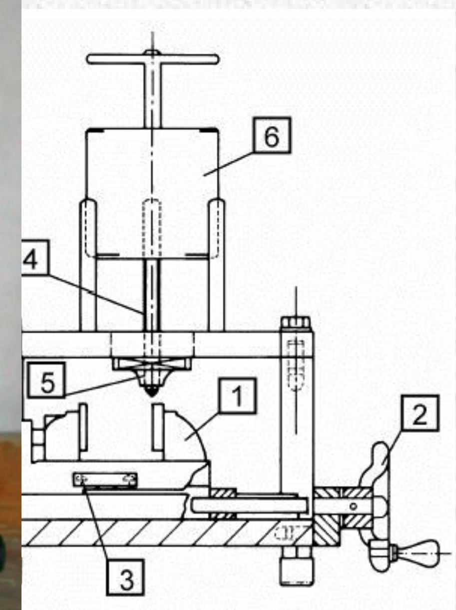
Tunneling parallel to foliation



Cerchar Abrasivity Test

Abrasivity Index (CAI) has proven to be fairly accurate and is commonly used for cutter life
estimation. A series of ... ulled across a freshly
broken surface of the ro... are related directly to
cutter life in field opera... ws calculation of the
expected cutter costs per

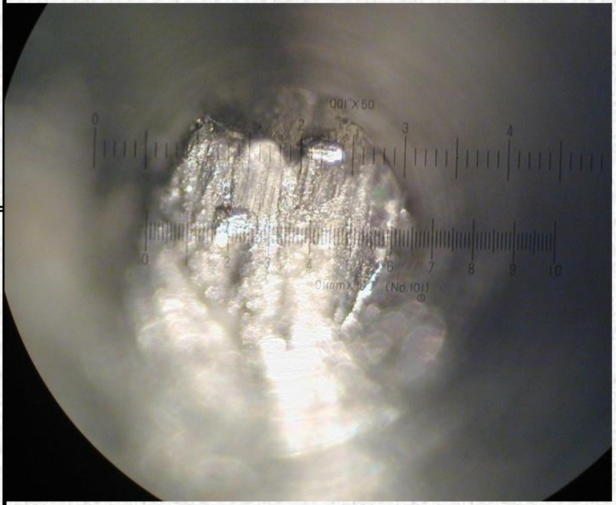


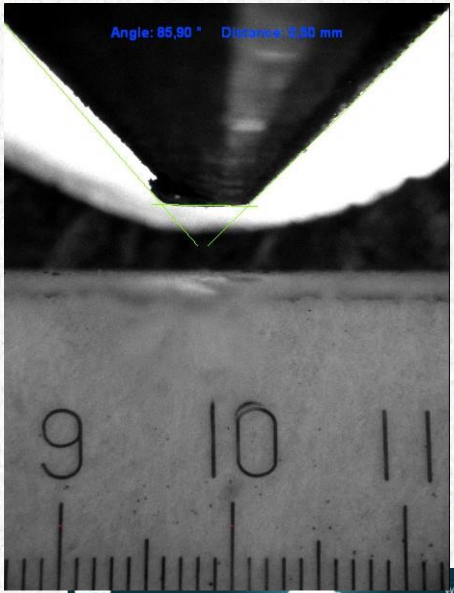


$i=1$

Cerchar Index

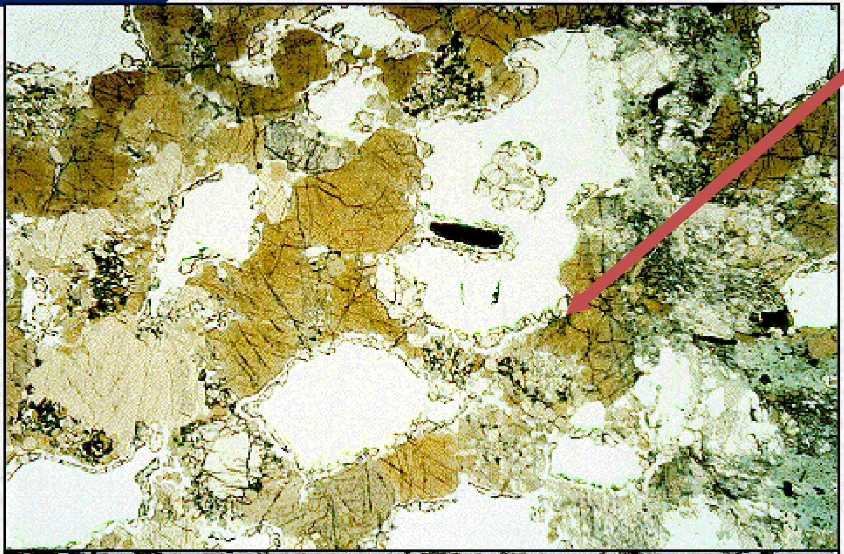
Category	NTNU Classification CAI (pin hardness 43)	CSM Classification CAI (pin hardness 56)
Not very abrasive or Non-Abrasive	0.3 - 0.5 “	< 1.0 ”
Slightly abrasive	0.5 - 1.0	1.0 - 2.0
Medium Abrasiveness to Abrasive	1.0 - 2.0 “	2.0 - 4.0 “
Very abrasive	2.0 - 4.0	4.0 - 5.0
Extremely abrasive	4.0 - 6.0	5.0 - 6.0
Quartzitic	6.0 - 7.0	

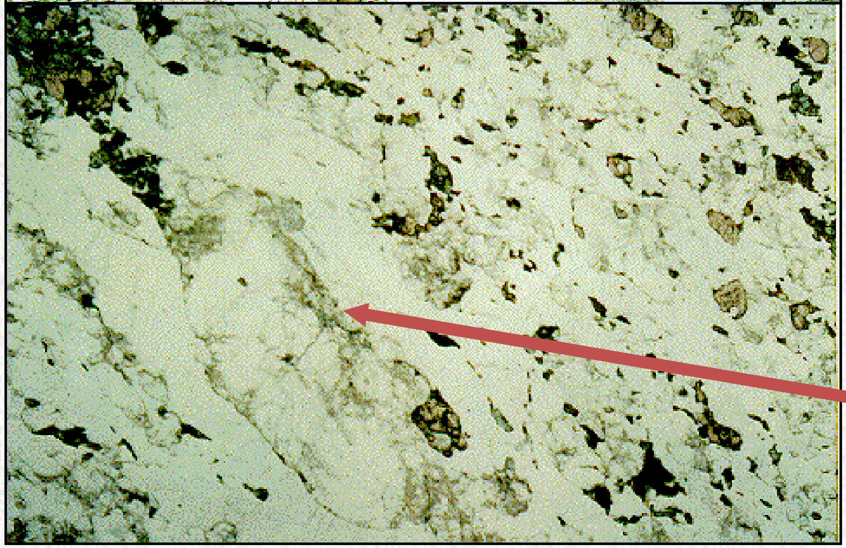




There has been much discrepancies in testing procedures about the pin hardness, surface conditions of the sample, measurement method, etc. that has caused problems, be careful in recording testing details

Thin-Section Petrographic Analysis (Suggested method by ISRM)





- Plane Polarized Light 20x.
- *Notice Garnet Wrapping*

The thin section analysis of rocks for engineering purposes includes the determination of parameters, which cannot be obtained from strength test of rock samples, such as mineral content, matrix characteristics grain size and texture. This analysis also helps identify any unusual rock microscopic features (i.e. grain suturing/interlocking, grain elongation), which may have an impact on its boreability.

- Plane Polarized Light, 20x
- *Notice Elongation*

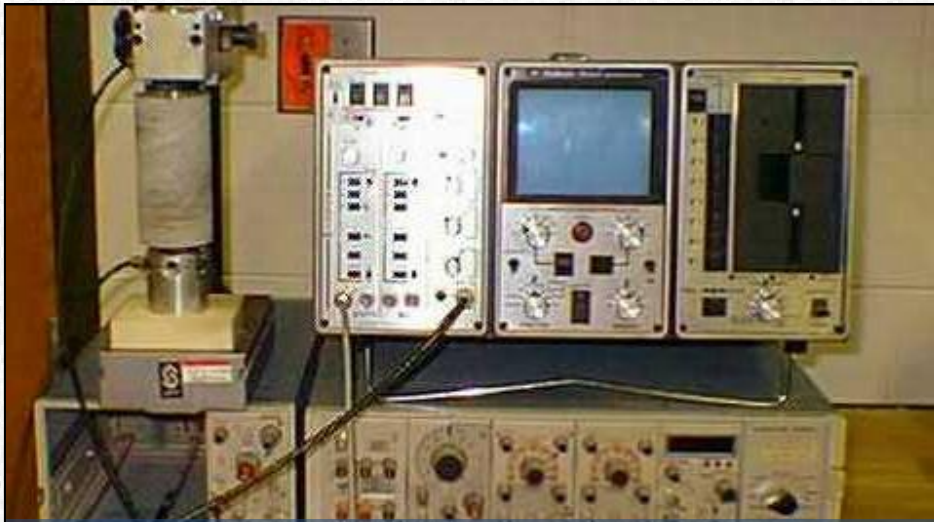
Acoustic Velocity (ASTM D2845-95)

- The velocities of compressive and shear ultrasonic waves through the core sample are measured and used to calculate the elastic modulus and Possion's ratio. This method indicates the compentecy of the rock.

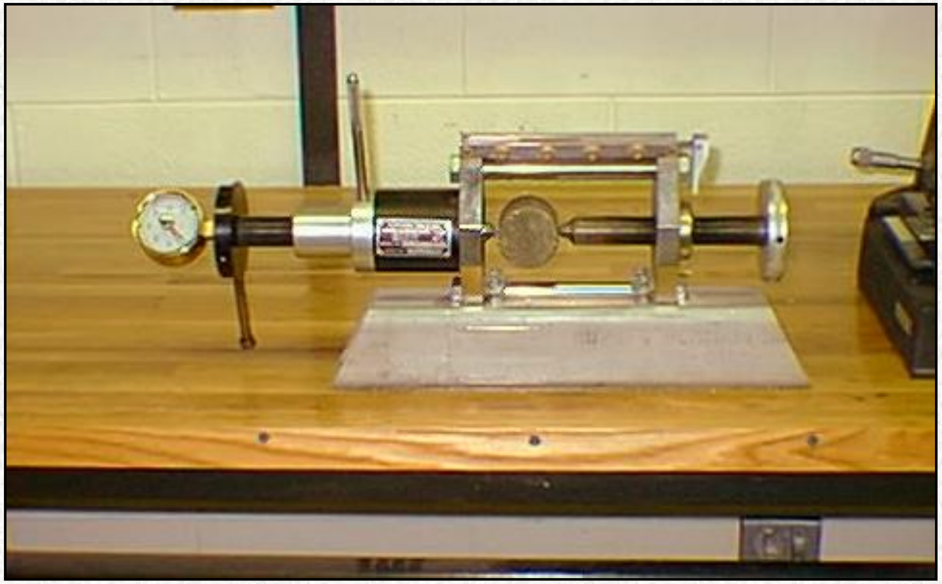
$$E = \frac{\rho V_S^2 \left(3V_P^2 - 4V_S^2\right)}{V_P^2 - V_S^2}$$

$$\mu = \frac{V_P^2 - 2V_S^2}{2\left(V_P^2 - V_S^2\right)}$$

V_S = Shear wave velocity (in./s or m/s)
V_P = Compressive wave velocity (in./s or m/s)
E = Elastic modulus (psi or Pa)
μ = Poisson's ratio
ρ = Density (lb/in^3 or kg/m^3)


Acoustic Velocity Test Set-up

Point Load Index (ASTM D5731)



$$I_S = \frac{F}{D_e^{\,2}}$$

Where

I_S ➔ Point load index (psi)

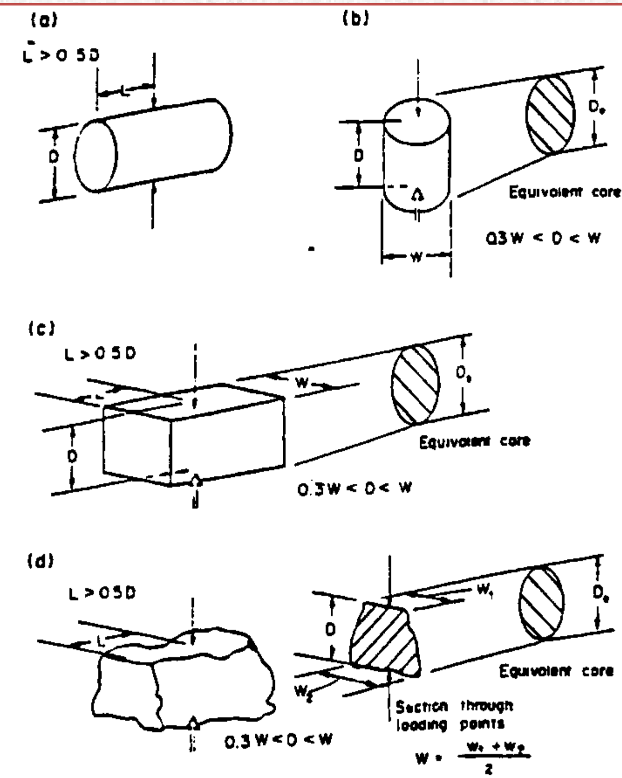
F ➔ Failure load (lbs.)

D_e ➔ Distance between platen tips (in.)

$D_e^2 = D^2$ ➔ for diametrical test

$= 4A/\pi$ ➔ for axial, block and lump test

A = W.D = minimum cross-sectional area of a plane through the platen contact points



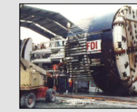
Specimen shape requirements for (a) the diametral test, (b) the axial test, (c) the block test, and (d) the irregular lump test.

Punch Penetration Test

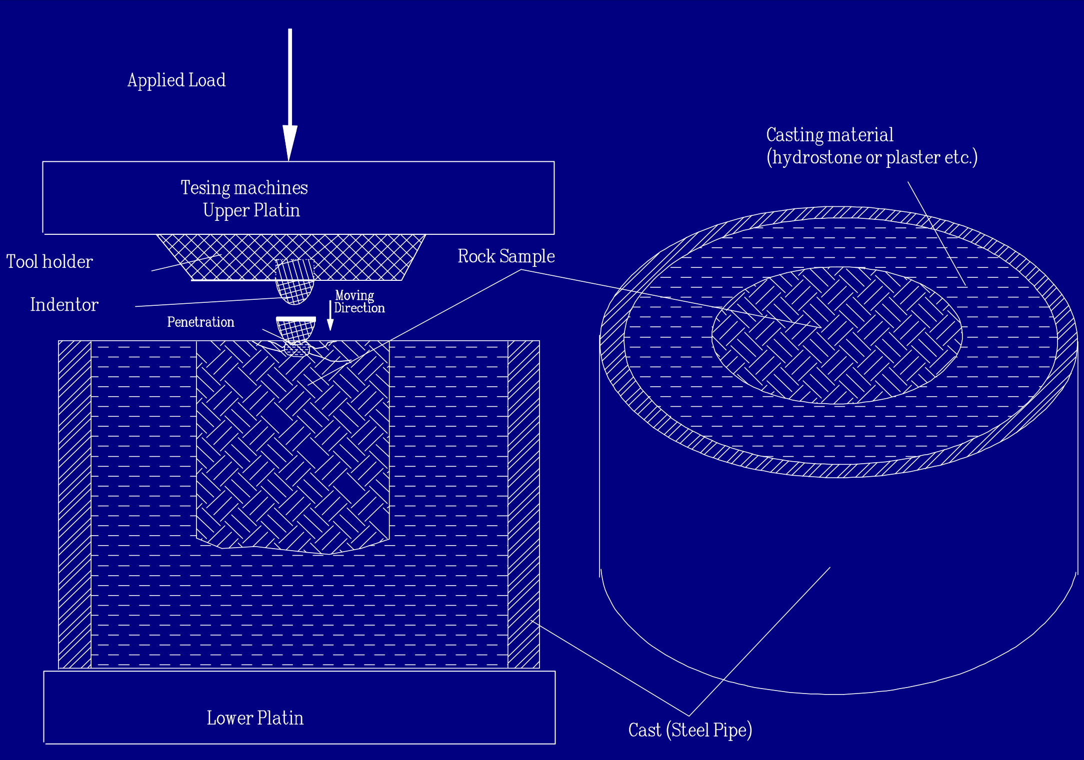
- In the Punch Penetration Index test, a standard indentor is pressed into a rock sample that has been cast in a confining ring. The load and displacement of the indentor are recorded with a computer system. The slope of the force-penetration curve indicates the excavatibility of the rock, i.e., the energy needed for efficient chipping.

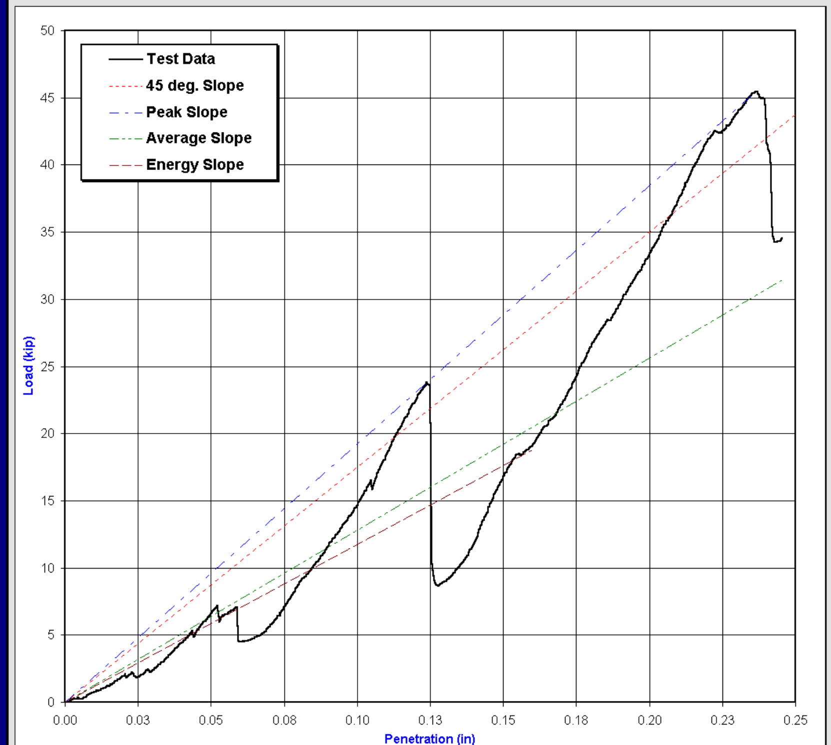
Earth Mechanics Institute
Colorado School of Mines

Punch Penetration Index Test



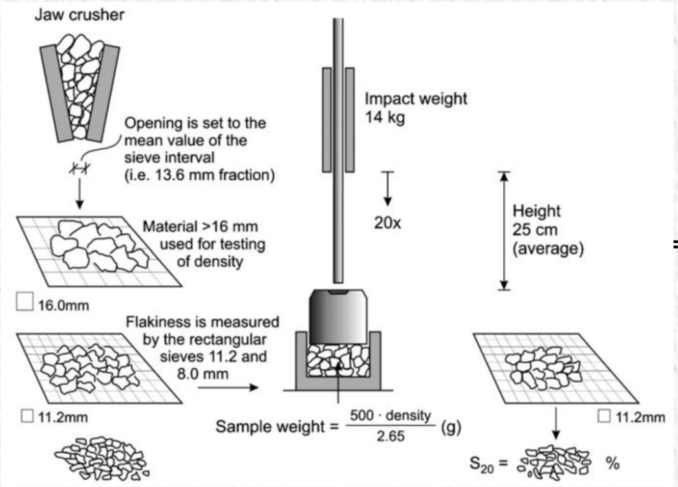
Project:	XYZ	Moisture Condition:	Air dried	
Location:	Golden	Penetration:	0.001	in/sec
Rock Type:	Igneous	Max. Load:	45,447	lbs
Rock Name:	granite			
Characteristics:	Massive			
Core ID:	BGP3			
File Name:	P3	45 Degree (Standard) Index:	175	
Test Performed by:	Mehmet	Peak Slope Index:	192	
Date Tested:	11/12/99	Average Slope Index :	128	
Data Reduced by:	Mehmet	Energy Slope Index:	117	
Date Reduced:	01/24/00			





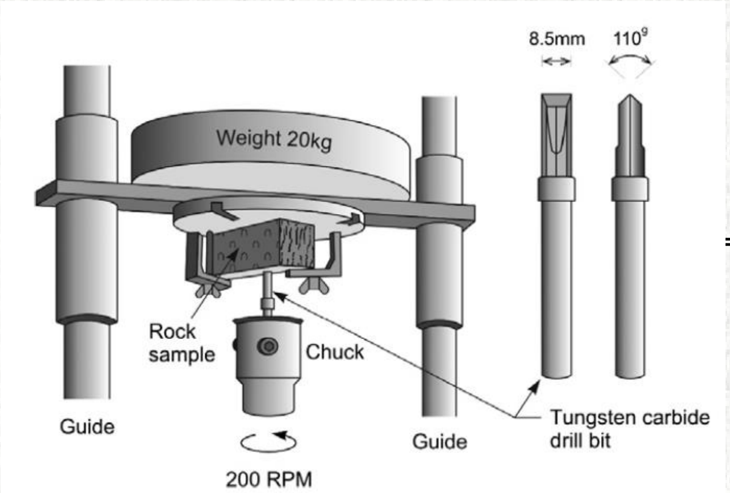
SINTEF / Norwegian Boreability Test Procedures and Apparatus

1. Brittleness Test



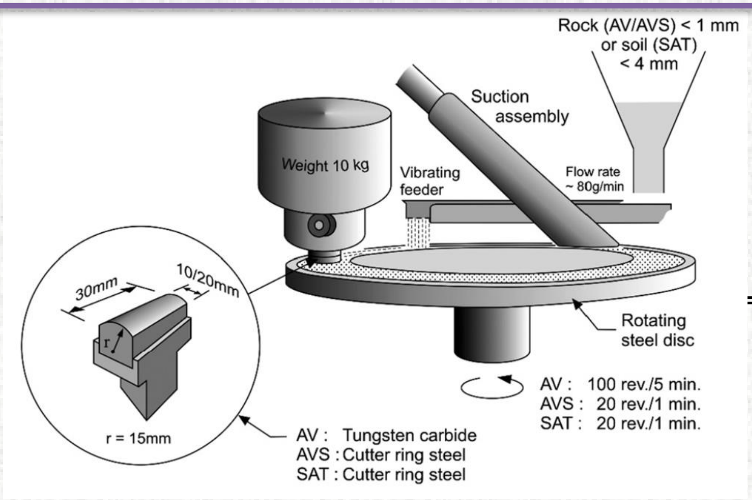
→ S_{20}

2. The Sievers' Miniature Drill Test



→ *SJ*

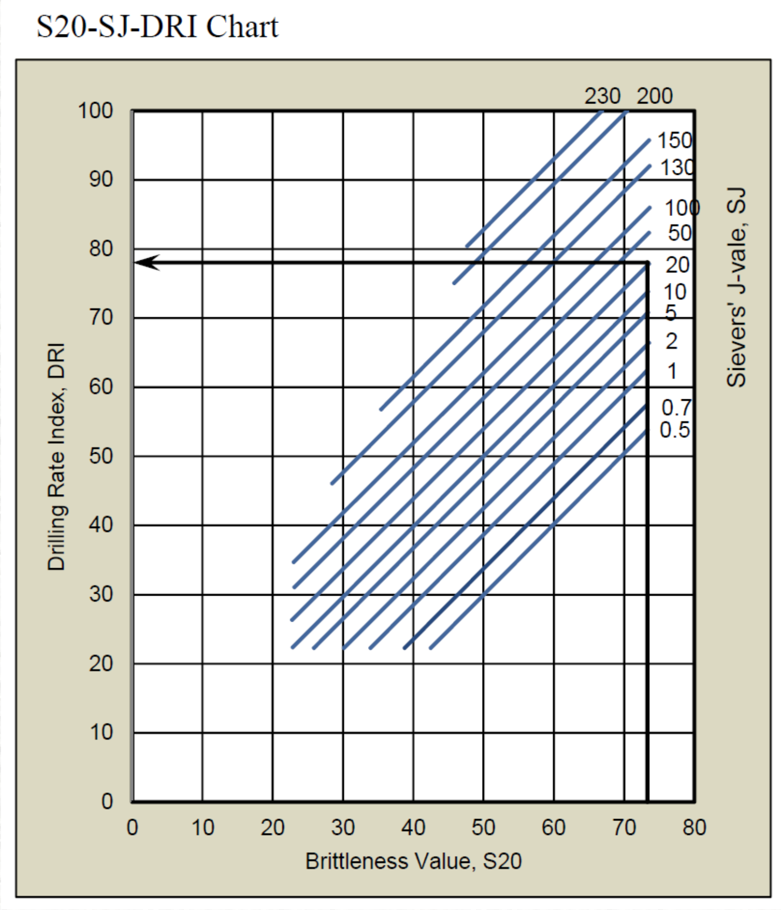
3. Abrasion Test



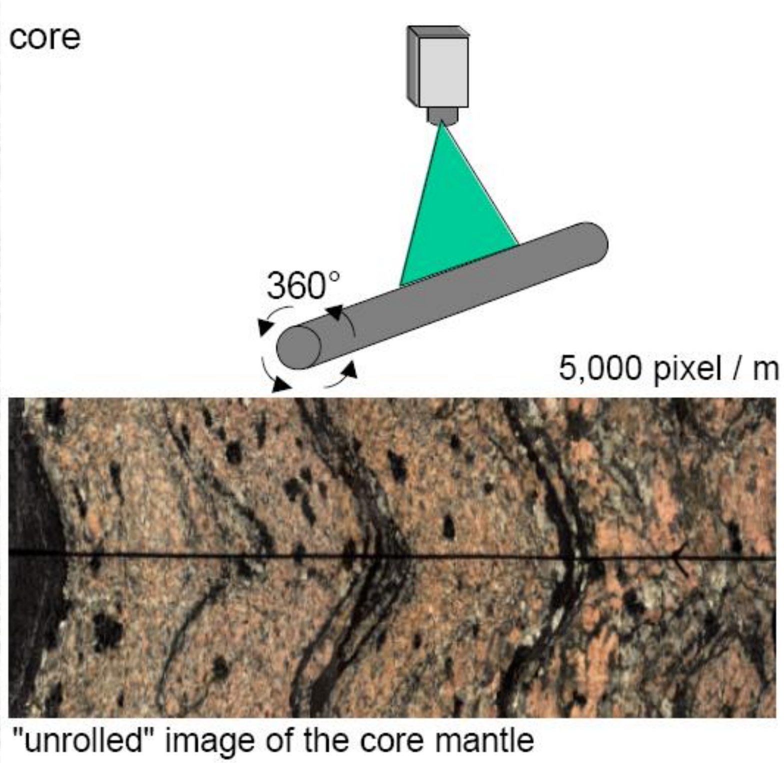
→ *AV (or ASV)*

SINTEF / Norwegian Boreability

- The tests yield three indices
  - Drilling Rate Index (DRI)
  - Cutter Life Index (CLI)
  - Bit Ware Index (BWI)
- Combined with joint info (spacing, orientation), and TBM specs and operational info, can be used for performance prediction



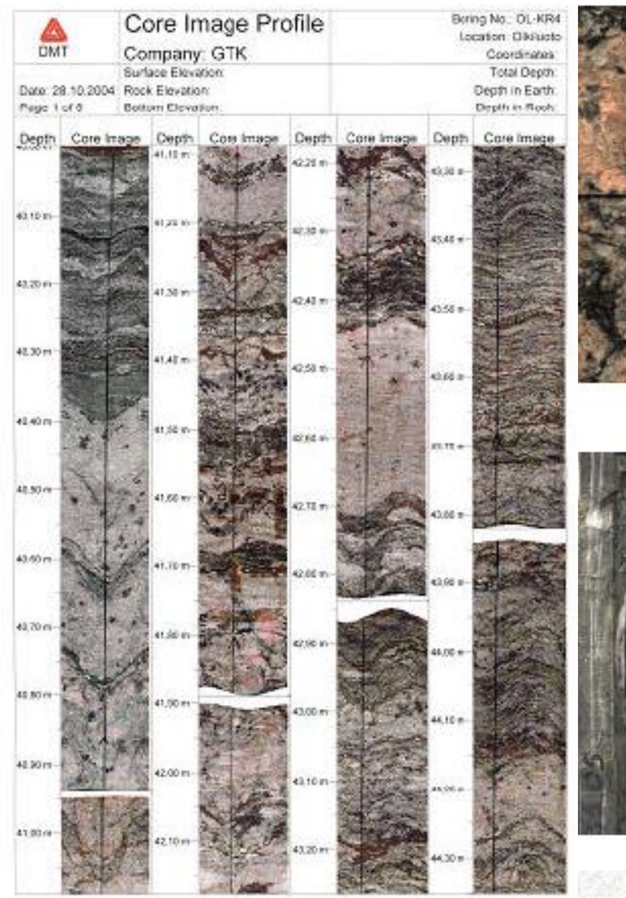
Core Scanning



Core Storage

Virtual Drill Core Library

Drill Core Storage House



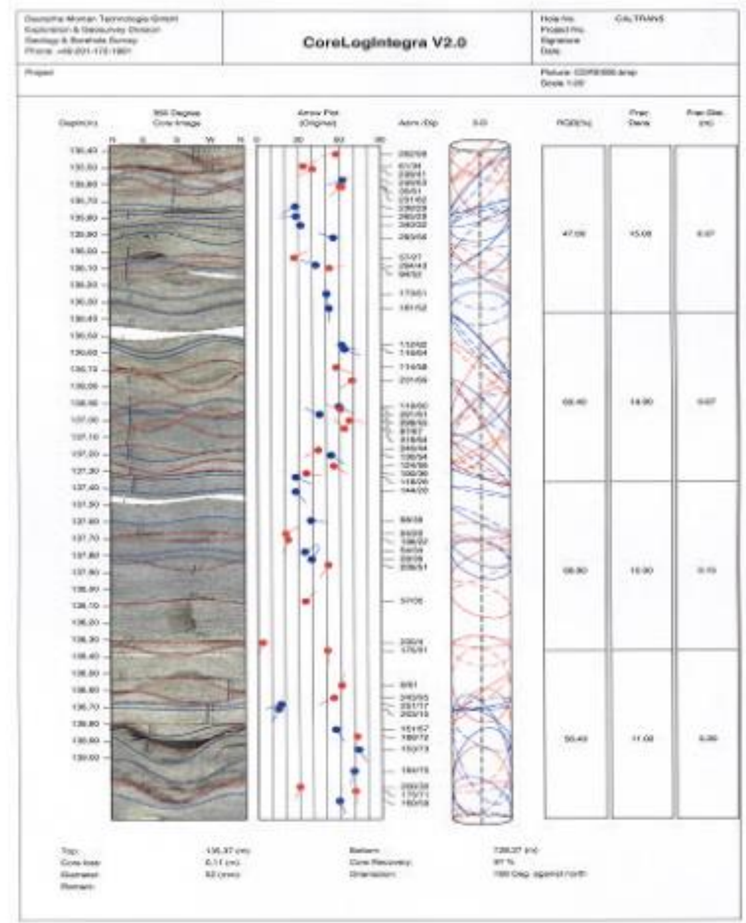
Virtual Drill Core Library

Core logs

CoreLog-Integra & Fracture Analysis™

Evaluation Software

- DMT CoreScan was developed for the use in both reservoir classes:
  - Fractured Reservoirs
  - Clastic Reservoirs
- Important parameters for the calculation of Fluid Flow of "fractured deposits" can be measured with CoreLog-Integra:
  - Geometric relationship of productive fractures (connectivity)
  - Quantifying the storage capacity
  - Visualisation of fracture distribution and locate productive fractures (aperture estimates, fracture characterisation at different scales)
- Fluid flow in "Fractured Reservoirs" is mainly based on quantitative derivation of required data from fracture orientation, fracture density and fracture spacing (estimates aperture).



In situ testing

- Logging boreholes to see voids/measurement of rock properties/joint density/joint orientation
  - Sonic/ acoustic /optical televiewers
- In-situ stresses measurement in rock, over-coring/fracing
- Pressure tests for in-situ Elastic property measurements
- Groundwater monitoring
    - Groundwater table, Perched/artesian aquifers need multiple level piezometers
    - Monitoring for extended period of time to see seasonal fluctuations,
    - Measuring permeability is critical, slug / pump tests
    - Check water salinity and flow rates for ground freezing

Geotech Cost, Reports and Risk Management for Tunneling Projects

Goetech Site Investigations

- Prospective and Interest
  - Owner (private, public, quasi-government)
  - Engineer / Designer
  - Contractor (single or joint)
  - Construction Management (CM)

Phases of Site Investigation

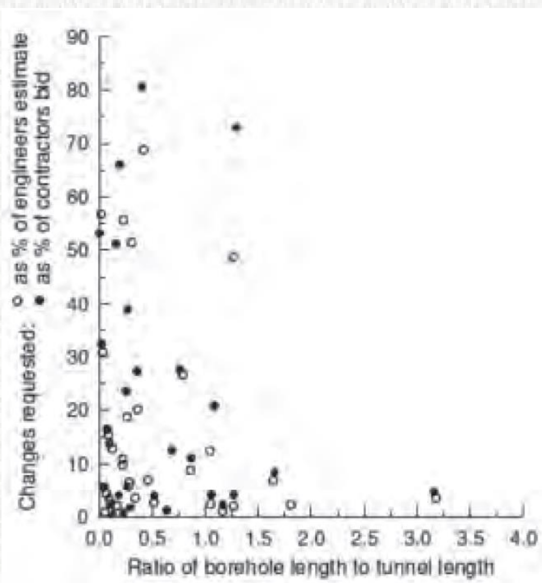
- Phase I – Feasibility
- Phase II – Preliminary Design
- Phase III – Final Design
- Phase IV – Construction

Geotechnical Reports

- Geotechnical Site Investigation Planning, typically at early design stage, never published
- Geotech Data Report (GDR), Contract documents
- Geotechnical Intepretive Report (GIR), contract doc, mostly for soil and shallow structures
- Geotechnical Data Summary Report (GDSR),
- Geotech Baseline Report (GBR), Contract document, higher risk more expensive projects, a risk sharing scheme, and a legal framework

Risk Assessment

- Geotech site investigation should be based on Risk Assessment and Risk Management
- This means being prepared for higher cost test where the consequence of missing a feature is very detrimental to the project



Risk Management

- **Can you or can you not live with your residual risks? Use a Risk Profile/Matrix to decide.**
- **(Use as a starter kit e.g. ISO Guide 51:1999 / ISO TS 14’798:2000)**

Risk Profile/Matrix[1] after implemented project measures

F Frequency (Hazard probability)	IV	III	II	I
A			7	
B				8
C			1	3
D	4			
E		6	2	
F				
	S[2] Severity (hazard effect category)			

Risk Profile/Matrix[1] *after additional measures*

F Frequency (Hazard probability)	IV	III	II	I
A				
B				
C			*7*	
D			*1*	*3, 8*
E	*4*		2	
F		*6*		
	S Severity (hazard effect category)			

S Severity (Hazard effect category)		F Frequency (Hazard probability)	
I	Death/system loss/severe environmental damage/financial loss > USD 10 M	A	Likely to occur **often**
II	**Irrecoverable** injury/irrecoverable illness/major system damage/ major environmental damage/financial loss <= USD 10 M	B	Will occur **several times** (more than once) in the life cycle of the system
III	**Recoverable** injury/recoverable illness/minor system damage/minor environmental damage/financial loss <= USD 1 M	C	Will occur **once** in the life cycle of the system
IV	Will **not** result in injury/illness/system damage/environmental damage/financial loss <= USD 0.1 M	D	Unlikely but **may possibly occur** in the life cycle of the system
Risk zones after preliminary hazard analysis/risk assessment => consequences:		E	So unlikely that it can be assumed **occurrence will not be experienced**
Red: Reduce risk; Yellow: Monitor risk; Green: No further measures required		F	The hazard incident cannot occur **unless caused by a deliberate act**

Residual Risks to be accepted[3]

No	First, summary explanation	No	First, summary explanation	No	First, summary explanation
3	State of the art				
8	Outside of systems' limits				

Planning Site Investigation for Tunneling

- Spacing of Borings: General Rule of Thumb!
  - For uniform and consistent grounds 0.7 ft/ft tunnel (m/m)
  - For typical ground conditions 1-1.5 ft/ft tunnel (m/m)
  - For very variable and changing grounds or for very sensitive structures 1.5-2 ft/ft tunnel (m/m)
  - Shafts need one boring at the center line and at least one more at the edge or preferably 2-3 on the periphery to identify transitions
  - For example for a 20,000 ft tunnel 30 ft dia.
    - If tunnel is shallow ~150 ft and in typical geology, go for 210 ft borings then we need 90 borings meaning average of ~200 ft interval
    - For a 500 ft deep tunnel in consistent geology, boring depth of 560 ft and we may need 27 borings at 750 ft interval.
  - Target to extend the borings 2D below invert
  - However, if the proposed vertical alignment is subject to modifications, it may be more economical to extend these depths to 3 times the tunnel diameter, for contingency purposes
  - Use inclined boring as needed

Cost of Geotech Investigation for Tunneling

- Reasonable range 3-7% total construction

Tunnel	Start of the works	Type	Total Length	Cumulated length of boreholes	Cost of explorations / cost of tunnel	Invest. Cost [M€]	Constr. method
Lötschberg	1994	Railway	34,6 km	N/A	2,8 %	N/A	Gripper TBM / DB
Gothard	1998	Railway	53,9 km	N/A	1,4 %	N/A	TBM / DB
Brenner	2011	Railway	57,0 km	~ 36 km	8,7 % I ncluding exploratory galleries	0,63	
LTF	Detailed design phase	Railway	57,1 km	~ 62 km	8,9 % ncluding exploratory galleries	1,08	
Koralm Base Tunnel	In construction		33 km	~ 21 km	1,9 %	0,64	N/A
Semmering Base Tunnel	In construction		27 km	~ 38,5 km	1,7 %	1,43	N/A

Tunnel	Start of the works	Type	Total Length	Cumulated length of boreholes	Cost of explorations / cost of tunnel	Invest. Cost [M€]	Constr. method
Saint Vallier	2002	Road	178 m	225 m	2,6 %	1,26	D&B
Schirmeck	2003	Road	550 + 150 m	704 m	3,7%	1,01	D&B
Bois du Peu	2004	Road	2*600 + 90 m	885 m	2,2% Excluding costs for exploratory gallery	1,09	D&B
Peute Combe	2009	Road	2*600 + 120 m	1219 m	3,85%	0,95	D&B
Saint Béat	2010	Road	110 + 310 m	1586 m	2,1%	1,12	D&B

Source: ITA work group #2 on Geotech Investigations

Summary

- Geotech Investigation for Tunnel and Underground Construction is more critical/sensitive than other construction projects
- Specialized tests are necessary, depending on construction method
- The lower the investment in Geotech investigations, the higher the probability and magnitude of the Claim
- Owners: Do not pressure the Geotech to reduce the budget, Pay back is a b…..
- Consultants/designers: Make sure to educate your clients, properly plan the Geotech work with sufficient time for proper investigation ahead of design
- Contractors: it is worthwhile to spend some money to identify the ground condition issues beforehand
- **Geotech Engineers, You are going to be blamed for all the construction problems no matter what!! :o)**





THANKS FOR YOUR ATTENTION

&

QUESTIONS