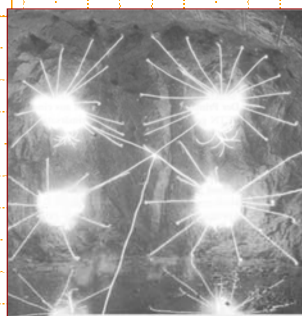


EOSC 547:

Tunnelling & Underground Design

Topic 4:

Hard Rock Tunnelling Methods

Tunnel Excavation in Rock

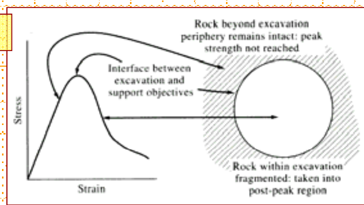
It is instructive to consider the fundamental objective of the excavation process – which is to remove rock material (either to create an opening or to obtain material for its inherent value). In order to remove part of a rock mass, it is necessary to induce additional fracturing and fragmentation of the rock.

This introduces three critical aspects of excavation:

- The peak strength of the rock must be exceeded.
- The *in situ* block size distribution must be changed to the required fragment size distribution.
- By what means should the required energy be introduced into the rock?

Tunnel Excavation in Rock

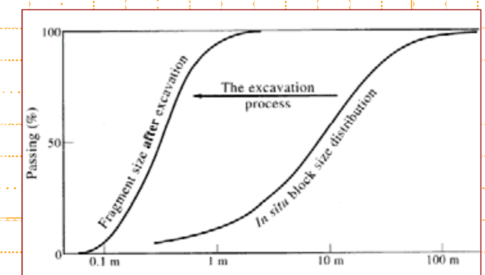
Strength



The tensile strength of rock is about 1/10th the compressive strength and the energy beneath the stress-strain curve is roughly its square. Therefore, breaking the rock in tension requires only 1/100th of the energy as that in compression.

Block size

The fracturing of rock during excavation changes the natural block size distribution to the fragment size distribution. The goal therefore is to consider how best to move from one curve to the other in the excavation process.

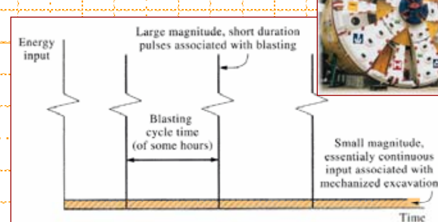


Hudson & Harrison (1997)

Energy and Excavation Process

One objective in the excavation process may be to optimize the use of energy, i.e. the amount of energy required to remove a unit volume of rock (specific energy = J/m^3). There are two fundamental ways of inputting energy into the rock for excavation:

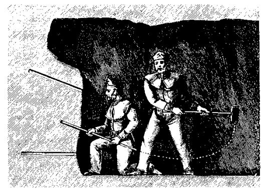
- Blasting: Energy is input in large quantities over very short durations (cyclical – drill then blast, drill then blast, etc.).



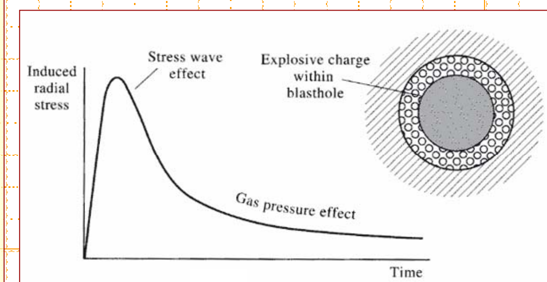
- Machine Excavation: Energy is input in smaller quantities continuously.

Drill & Blast

The technique of rock breakage using explosives involves drilling blastholes by percussion or rotary-percussive means, loading the boreholes with explosives and then detonating the explosive in each hole in sequence according to the blast design.

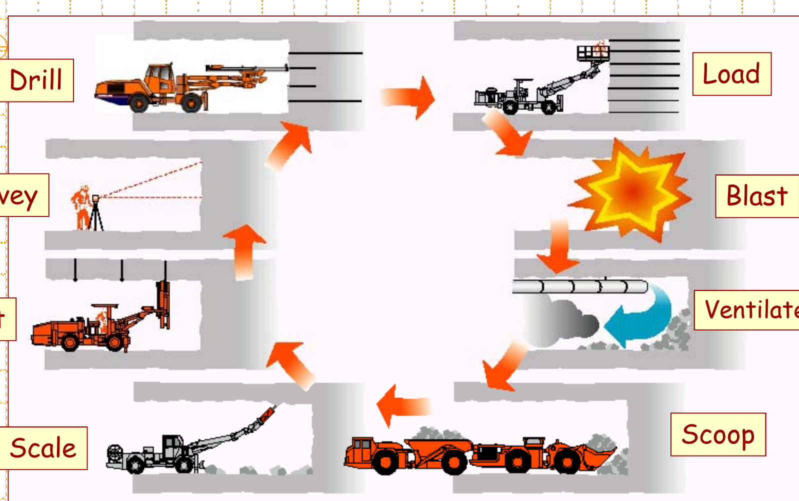


The explosion generates a stress wave and significant gas pressure. Following the local fracturing at the blasthole wall and the spalling of the free face, the subsequent gas pressure then provides the necessary energy to disaggregate the broken rock.

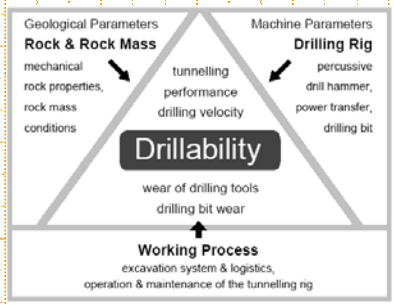


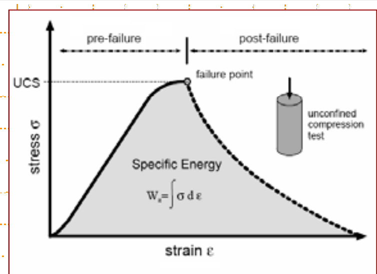
Hudson & Harrison (1997)

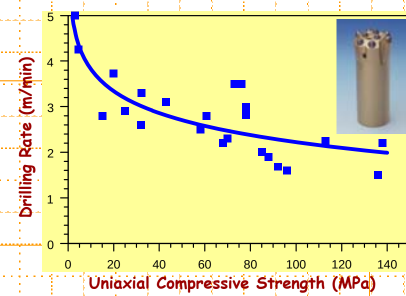
Conventional Drill & Blast Cycle

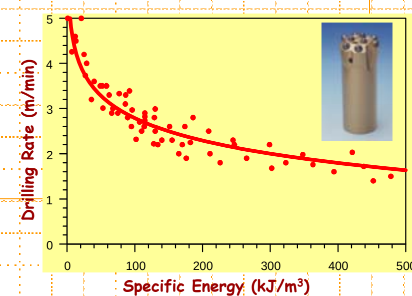


Drill & Blast – Drilling Rates



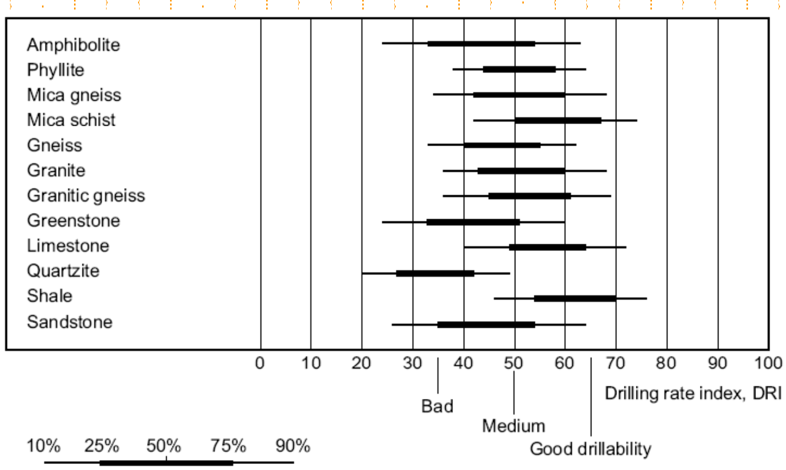






Thuro & Plinninger (2003)

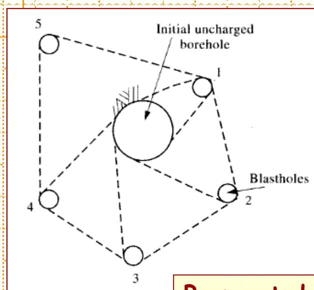
Drill & Blast – Drilling Rates

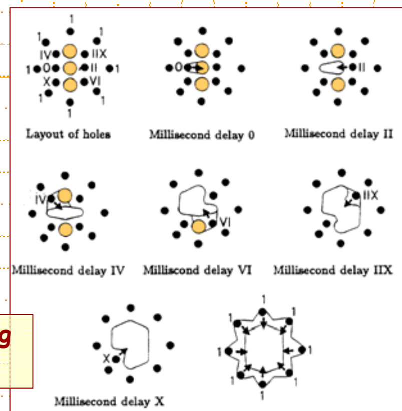


UNIT-NTH (1995)

Blasting Rounds – Burn Cut

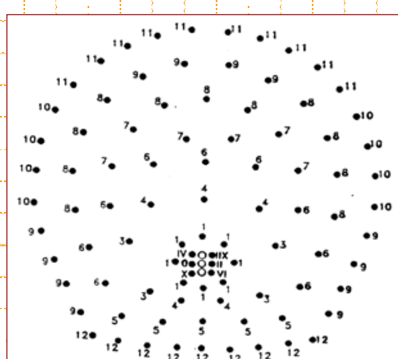
The correct design of a blast starts with the first hole to be detonated. In the case of a tunnel blast, the first requirement is to create a void into which rock broken by the blast can expand. This is generally achieved by a wedge or burn cut which is designed to create a clean void and to eject the rock originally contained in this void clear of the tunnel face.

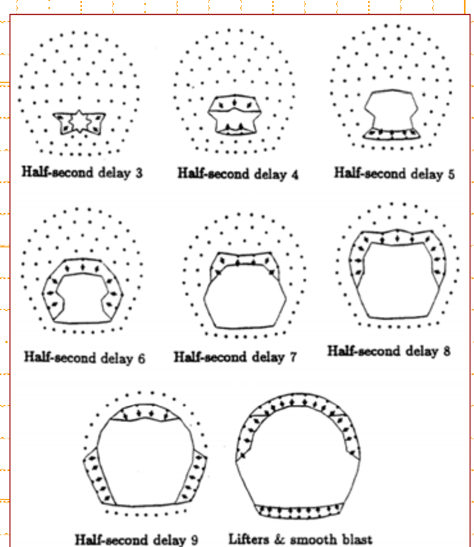




Burn cut designs using millisecond delays.

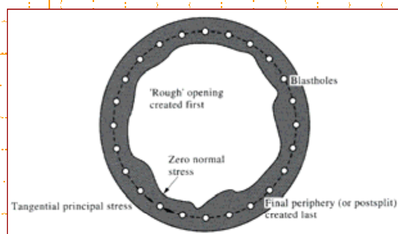
Blasting Rounds – Blast Pattern Design

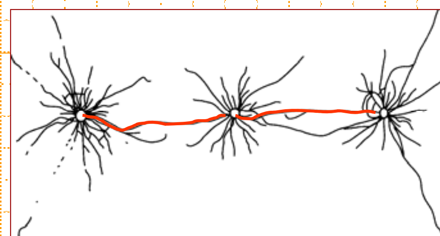




Specialized Blasting Techniques

During blasting, the explosive damage may not only occur according to the blasting round design, but there may also be extra rock damage behind the excavation boundary. To minimize damage to the rock, a smooth-wall blast may be used to create the final excavation surface.

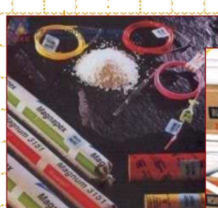




Hudson & Harrison (1997)

The smooth-wall blast begins by creating a rough opening using a large bulk blast. This is followed by a smooth-wall blast along a series of closely spaced and lightly charged parallel holes, designed to create a fracture plane connecting the holes through by means of coalescing fractures.

Blasting Accessories



Explosives

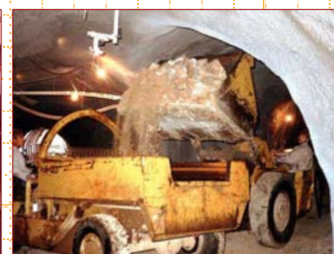
Delays: used to orchestrate rotational firing.

Primacord: ignition velocity is approx. 6,400 m/s.

Safety fuse: Gives miner time to light all fuses and still have time to seek safety before the blast occurs.

Blasting Rounds – Fragmentation

How efficiently muck from a working tunnel or surface excavation can be removed is a function of the blast fragmentation. Broken rock by volume is usually 50% greater than the *in situ* material. In mining, both the ore and waste has to be moved to surface for milling or disposal. Some waste material can be used underground to backfill mined voids. In tunnelling, everything has to be removed and dumped in fills – or if the material is right, may be removed and used for road ballast or concrete aggregate (which can sometimes then be re-used in the tunnel itself).

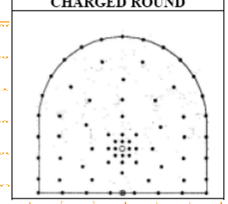


Blasting – Summary

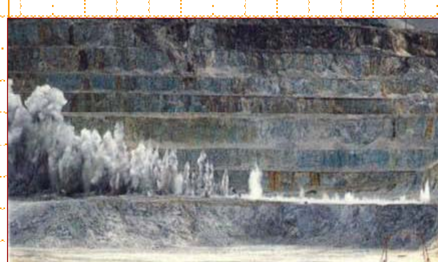
CONTROLLABLE VARIABLES		
DRILLING	CHARGING	BLASTING
- Diameter drill hole - Drilled length - Drill pattern - Incorrect drilling	- Type of explosives - Energy of explosives - Charging method - Design of charging - Charged length - Firing pattern	- Firing system - Firing interval - Water (partly)

NON-CONTROLLABLE VARIABLES	
GEOLOGY	OTHER
- Rock parameters - Rock mass joint	- Incline/Decline - Water (partly)

CHARGED ROUND



Typical production round fires in less than 7 seconds

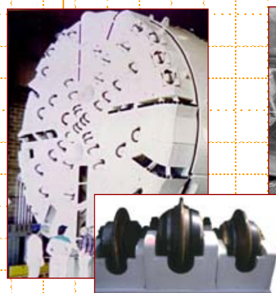


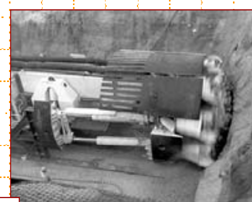
RESULT
- Fragmentation - Throw - Muck pile shape - Loadability - Vibrations - Advance per round - Contour - Flyrock - Non-detonating holes - Poor blast result

NTNU (1995)

Mechanical Excavation in Rock

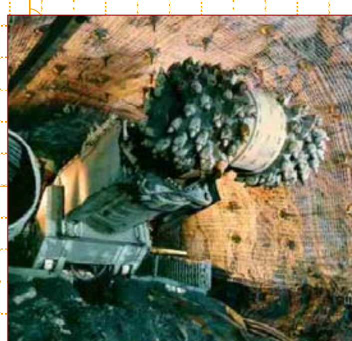

Tunnel Boring Machine (TBM)





Mechanical Excavation in Rock

There are two basic types of machine for underground rock excavation:

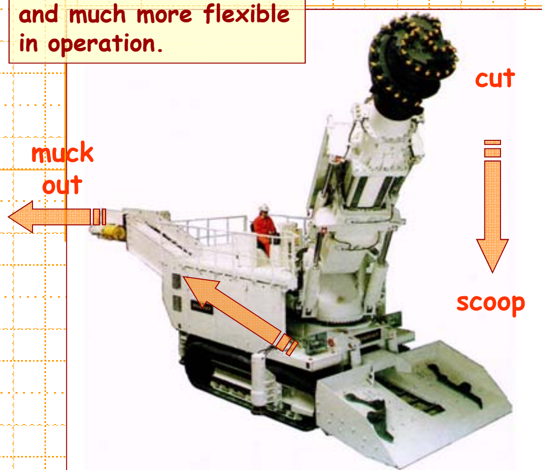


<u>Partial-face machines</u>: use a cutting head on the end of a movable boom (that itself may be track mounted).

<u>Full-face machines</u>: use a rotating head armed with cutters, which fills the tunnel cross-section completely, and thus almost always excavates circular tunnels.

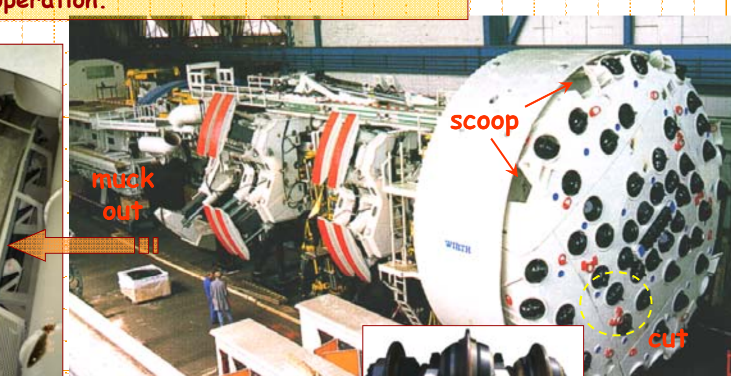
Mechanical Excavation in Rock

Partial-face machines are cheaper, smaller and much more flexible in operation.



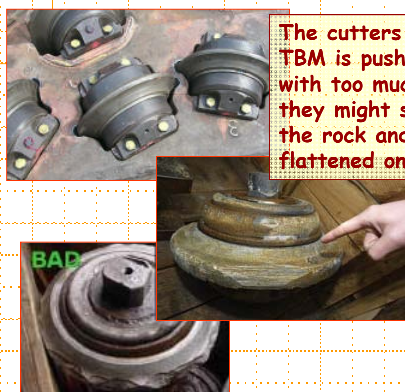
Mechanical Excavation in Rock

Full-face machines – when used for relatively straight and long tunnels (>2 km) – permit high rates of advance in a smooth, automated construction operation.



Mechanical Excavation

The advance rate at which the excavation proceeds is a function of the cutting rate and utilization factor (which is the amount of time that the machine is cutting rock). Factors contributing to low utilization rates are difficulties with ground support and steering, the need to frequently replace cutters, blocked scoops, broken conveyors, etc.



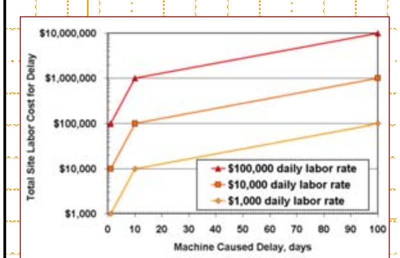
The cutters may jam if the TBM is pushed forwards with too much force. Then they might scrape against the rock and become flattened on one side.

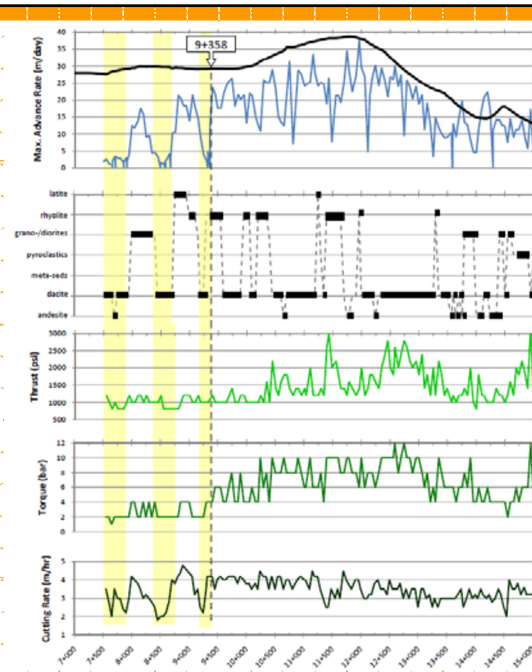
Broken conveyor

TBM Operation

Factors that may control TBM performance include:

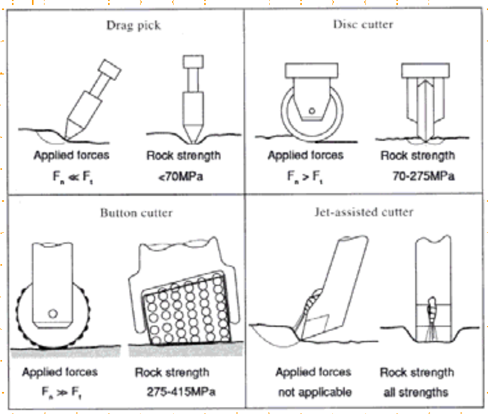
- TBM Penetration Rate (meters/machine hour)
- TBM Downtime (minutes)
- TBM Utilization (machine hours/shift hours)
- Tool Wear (tool changes per shift)





Mechanics of Rock Cutting

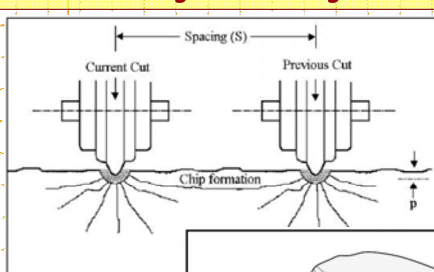
In tunnelling terms, a TBM applies both thrust (F_n) and torque (F_t) during the cutting process. In selecting the proper cutting tool, the engineer wishes to know how the tools should be configured on a machine cutting head, how to minimize the need to replace cutters, how to avoid damaging the cutter mounts, and how to minimize vibration.

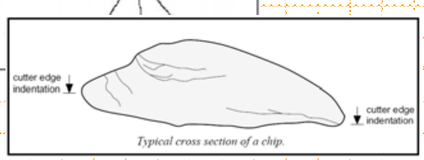


Hudson & Harrison (1997)

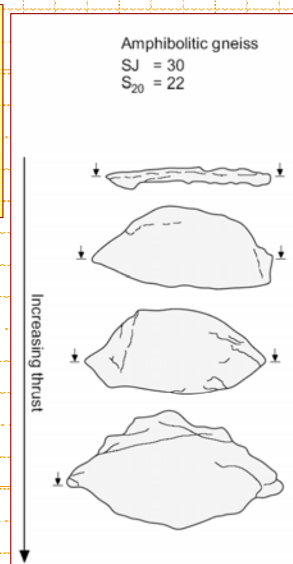
Mechanics of Rock Cutting

Cutting involves a complex mixture of tensile, shear and compressive modes of failure. With thrust, the cutting disc penetrates the rock and generates extensive crack propagation to the free surface. Further strain relief occurs as the disc edge rolls out of its cut, inducing further tensile cracking and slabbing at the rock surface.





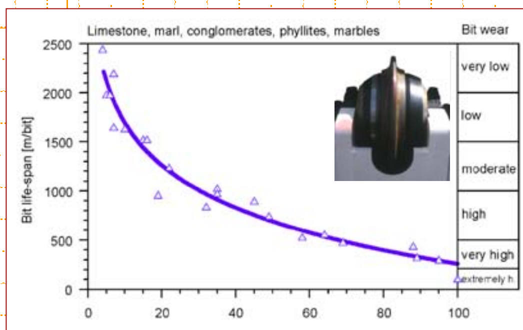
Typical cross section of a chip.



NTNU-Anleggsdrift (1998)

Mechanics of Rock Cutting – Cutter Wear

The primary impact of disc wear on costs can be so severe that cutter costs are often considered as a separate item in bid preparation. In general, 1.5 hours are required for a single cutter change, and if several cutters are changed at one time, each may require 30-40 minutes. Even higher downtimes can be expected with large water inflows, which make cutter change activities more difficult and time-consuming.



Mechanical Excavation – Cutter Heads

Delays: When the tunnel boring machine is inside the tunnel, the cutters must be changed from the inside the cutting head.

Mechanical Excavation – Cutter Heads

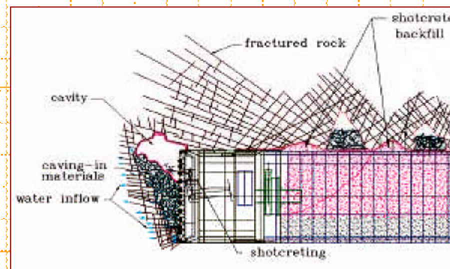
Mechanical Excavation – Cutter Heads

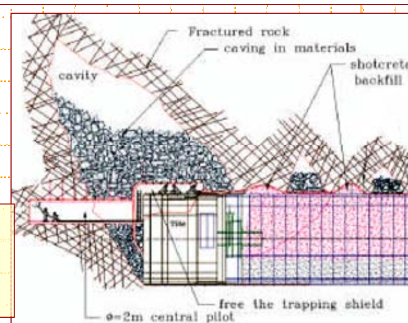
Mechanical Excavation – Cutter Heads

Mechanical Excavation – Cutter Heads

TBM Excavation & Design

The two main factors that will stop tunnel boring machines are either the rock is too hard to cut or that the rock is too soft to sustain the reactionary force necessary to push the machine forward. TBM's will operate within certain ranges of rock deformability and strength, where the machine can be tailored to a specific range to achieve maximum efficiency (the risk being if rock conditions diverge from those the TBM is designed for) .





Instability problems at the tunnel face, encountered during excavation of the 12.9km long Pinglin tunnel in Taiwan.

Barla & Pelizza (2000)

TBM Excavation & Design

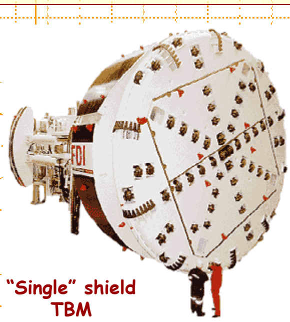
Table 1 : General classification scheme for tunnelling machines (AITES / ITA, Working Group No.14).

Support				Excavation		Reaction Force	Machine	
Location	System: Cavity	System: Face		Method	Tool		Category	Type
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

Barla & Pelizza (2000)

TBM Excavation & Design

Single & Double Shield TBM's – Single-shield TBM's are cheaper and are the preferred machine for hard rock tunnelling. Double shielded TBMs are normally used in unstable geology (as they offer more worker protection), or where a high rate of advancement is required.



"Single" shield TBM

"Double" shield TBM

TBM Excavation & Design

Impacts of Geotechnical Conditions on TBM Operations

Major Geotechnical Conditions	Consequences/Requirements
Loosening loads, blocky/slabby rock, overbreak, cave-ins	At the face: cutterhead jams, disc impact loading, cutter disc and mount damage possible, additional loss on available torque for cutting, entry to the face may be required with impact on equipment selection, recessed cutters may be recommended for face ground control. In the tunnel: short stand-up time, delays for immediate and additional support (perhaps grouting, hand-mining), special equipment (perhaps machine modifications), gripper anchorage and steering difficulty, shut-down in extreme cases of face and crown instability. Extent of zones (perhaps with verification by advance sensing/probe hole drilling) may dictate shield required, and potential impact on lining type selection (as expanded segmental linings may not be reasonable), grouting, and backpacking time and costs may be high.
Groundwater inflow	Low flow/low pressure - operating nuisance, slow-down, adequate pumping capability high flow and/or high pressure - construction safety concerns, progress slow or shut-down, special procedures for support and water/wet muck handling, may require advance sensing/probe hole drilling. Corrosive or high-salt water - treatment may be required before disposal, equipment damage, concrete reactivity, problems during facility operation. Equipment modifications (as water-proofing) may be required if inflow is unanticipated - significant delays.

U.S. Army Corps of Engineers (1997)

TBM Excavation & Design

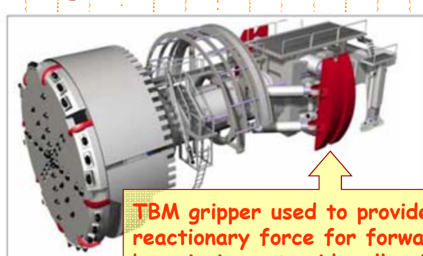
Impacts of Geotechnical Conditions on TBM Operations

Major Geotechnical Conditions	Consequences/Requirements
Squeezing ground	Shield stalling, must determine how extensive and how fast squeeze can develop, delays for immediate support, equipment modifications may be needed, if invert heave and train mucking - track repair and derail downtime.
Ground gas/hazardous fluids/wastes	Construction safety concerns, safe equipment more expensive, need increased ventilation capacity, delays for advance sensing/probing and perhaps project shut-down, special equipment modifications with great delays if unanticipated, muck management and disposal problems.
Overstress, spalls, bursts	Delays for immediate support, perhaps progress shut-down, construction safety concerns, special procedures may be required.
Hard, abrasive rock	Reduced *PRev* and increased F_n - TBM needs adequate installed capacities to achieve reasonable advance rates, delays for high cutter wear and cutterhead damage (especially if jointed/fractured), cutterhead fatigue, and potential bearing problems
Mixed-strength rock	Impact disc loading may increase failure rates, concern for side wall gripping problems with open shields, possible steering problems.
Variable weathering, soil-like zones, faults	Slowed progress, if sidewall grippers not usable may need shield, immediate and additional support, potential for groundwater inflow, muck transport (handling and derails) problems, steering difficulty, weathering particularly important in argillaceous rock.
Weak rock at invert	Reduced utilization from poor trafficability, grade, and alignment - steering problems.

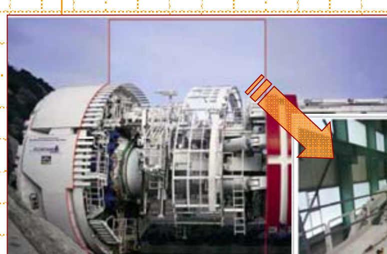
U.S. Army Corps of Engineers (1997)

TBM Excavation & Design

TBM insertion through vertical shaft.



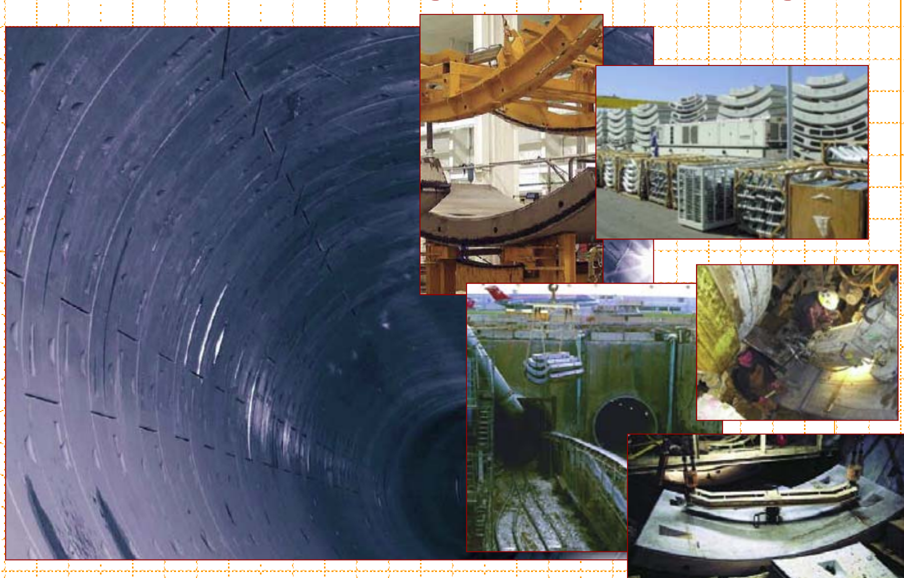
TBM gripper used to provide reactionary force for forward thrust by gripping onto sidewalls of tunnel.



TBM working platform for installing support (e.g. rock bolts, meshing, shotcrete).

TBM Operation

TBM Excavation & Design - Pre-Cast Linings



Tunnelling Breakthroughs

TBM Selection & Geological Risk

The Yacambú-Quibor Tunnel is a prime example of tunnelling blind – the geology was largely unfamiliar and unpredictable. With little previous experience, it was unknown how the rock would react, especially under the high stresses of the Andes.

Geology: Weak, tectonically sheared graphitic phyllites were encountered giving rise to serious squeezing problems, which without adequate support would result in complete closure of the tunnel.

1975: Excavation begins on the 24 km tunnel, for which the use of a full-face TBM is specified (for rapid excavation).

1977: The weak phyllites fail to provide the TBM grippers with enough of a foundation to push off of. Supporting squeezing ground was another defeating problem.

1979: During a holiday shutdown, squeezing rock conditions were left unchecked, resulting in the converging ground effectively "swallowing" one of the TBMs.

1980's: A decision is made to permit the tunnel to be excavated by drill & blast. Recently completed, it took more than 33 years to tunnel the full 24 km.

Mining out the remains of the trapped TBM.

Hoek (2001)

Sequential Excavation & Design - Benches

Benched excavations are used for large diameter tunnels in weak rock. The benefits are that the weak rock will be easier to control for a small opening and reinforcement can be progressively installed along the heading before benching downward. Variations may involve sequences in which the inverts, top heading and bench are excavated in different order.

Lecture References

Barla, G & Pelizza, S (2000). TBM Tunneling in difficult conditions. In *GeoEng2000, Melbourne*. Technomic Publishing Company: Lancaster, pp. 329-354.

Harding, H (1981). "Tunnelling History and My Own Involvement". Golder Associates: Toronto, 258pp.

Hudson, JA & Harrison, JP (1997). "Engineering Rock Mechanics – An Introduction to the Principles ". Elsevier Science: Oxford, 444pp.

Maidl, B, Herrenknecht, M & Anheuser, L (1996). "Mechanised Shield Tunnelling". Ernst & Sohn: Berlin, 428pp.

NTNU (1995). "Tunnel: Blast Design". Department of Building and Construction Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Project Report 2A-95.

NTNU-Anleggsdrift (1998). "Hard Rock Tunnel Boring: The Boring Process". Norwegian University of Science and Technology (NTNU), Trondheim, Project Report 1F-98.

Thuro, K & Plinninger, RJ (2003). Hard rock tunnel boring, cutting, drilling and blasting: rock parameters for excavatability. In: Proc., 10th ISRM Congress, Johannesburg. SAIMM: Johannesburg, pp. 1227-1234.

UNIT-NTH (1995). "Tunnel: Prognosis for Drill and Blast". Department of Building and Construction Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Project Report 2B-95.

Whittaker, BN & Frith, RC (1990). "Tunnelling: Design, Stability and Construction". Institution of Mining and Metallurgy: London, 460pp.