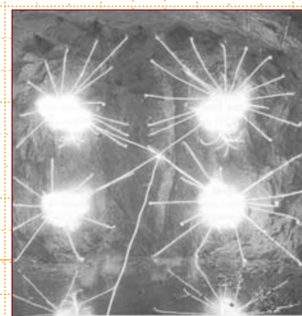
EOSC433:

Geotechnical Engineering Practice & Design



Lecture 6: Excavation Methods

The Excavation Process

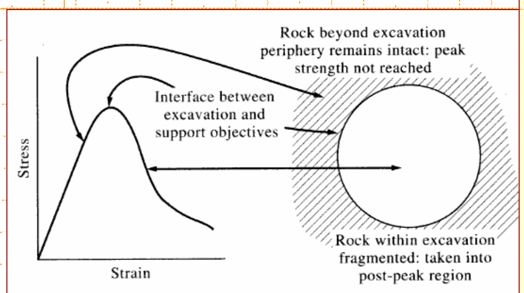
It is instructive to consider the fundamental objective of the excavation process – which is to remove rock material (either to create an opening or to obtain material for its inherent value). In order to remove part of a rock mass, it is necessary to induce additional fracturing and fragmentation of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

Attaining Post-Peak Behaviour

In order to provide the necessary large-scale fragmentation, a part of the intact rock must be taken into the post-peak portion of the complete stress-strain curve. At the same time, we wish to remain in the pre-peak portion of the curve for rock stability around the excavation periphery. It follows that an excavation boundary is an interface between two fundamentally different engineering objectives and materials.

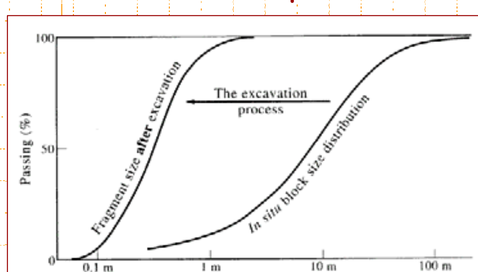


Hudson & Harrison (1997)

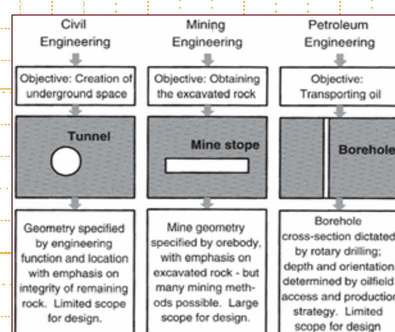
Because the tensile strength of rock is about 1/10th the compressive strength and the energy beneath the stress-strain curve is roughly its square, breaking the rock in tension requires only 1/100th of the energy as that in compression. So, not only do we need to match the fragmentation process (e.g. explosive) to the rock type, but we need to consider carefully how to use the energy in an optimal way.

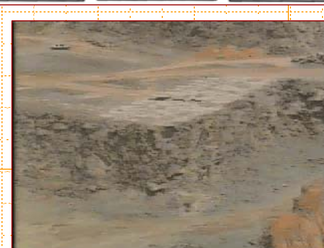
In Situ Block and Fragmentation Distribution

Rock is naturally fractured and consists of rock blocks of certain sizes. The fracturing of rock during excavation changes this natural block size distribution to the fragment size distribution. The engineer can consider how best to move from one curve to the other in the excavation process.



Hudson & Harrison (1997)

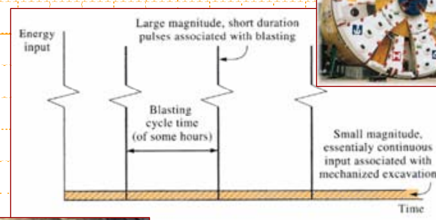


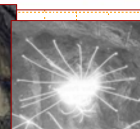


Energy and Excavation Process

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:

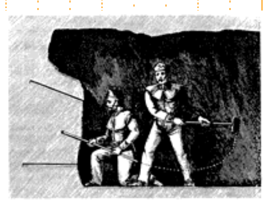
- **Blasting**: Energy is input in large quantities over very short durations (cyclical – drill then blast, drill then blast, etc.).
- **Machine Excavation**: Energy is input in smaller quantities continuously.



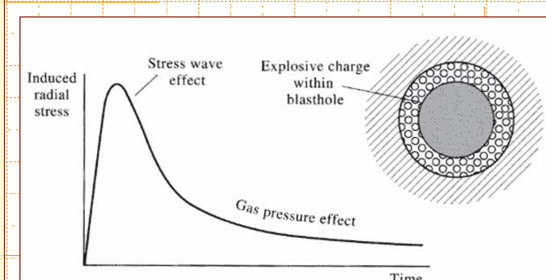


Drill & Blast

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.

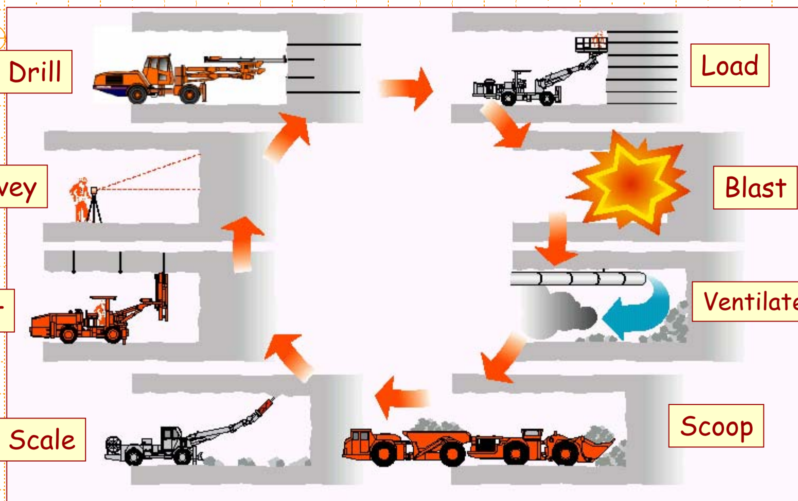


The explosion generates a stress wave and significant gas pressure. Following the local fracturing at the blasthole wall and the spalling of the free face, the subsequent gas pressure then provides the necessary energy to disaggregate the broken rock.

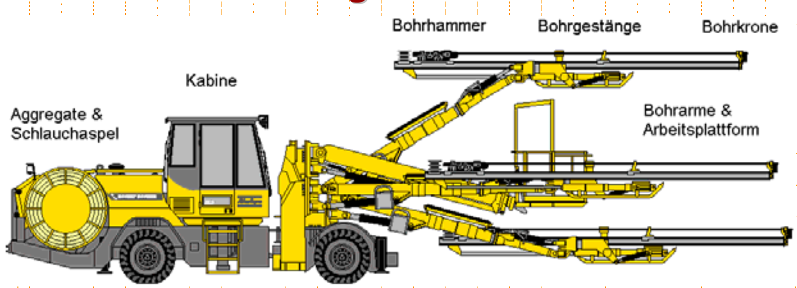


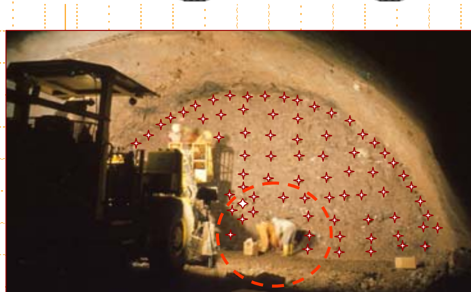
Hudson & Harrison (1997)

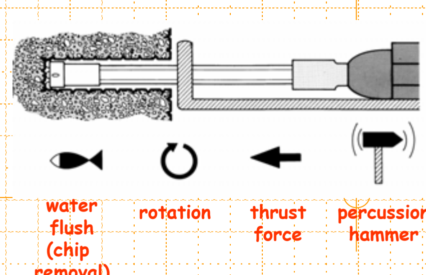
Conventional Drill & Blast



Drill & Blast - Drilling







Drill & Blast - Drilling

Three parameters should be considered when choosing a drill bit: penetration rate, hole straightness and service life. In 95% of all rock drilling, a button bit is selected to drill the hole to a given diameter.

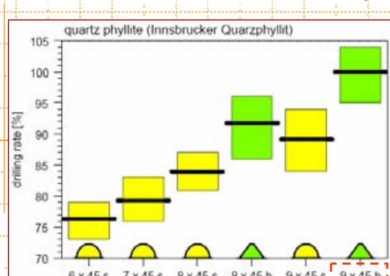


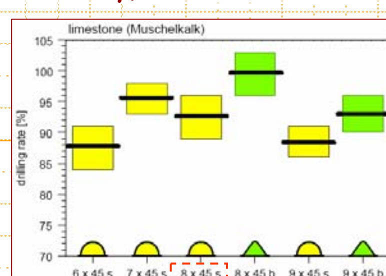
Button Shape	Characteristics	Application
Spherical	· "non aggressive" shape · minimum drilling rates · low bit wear · excavation mainly by impact	Rock with high UCS and high abrasivity (e.g. quartzite, granite, gneiss, amphibolite)
Semi-Ballistic	· "aggressive" shape · moderate drilling rates · moderate bit wear · excavation mainly by shearing/cutting	Rock with mid UCS and less abrasivity (e.g. slate, sandstone, limestone, weathered rock)
Conical (Ballistic)	· "very aggressive" shape · maximum drilling rates · high bit wear · excavation mainly by shearing/cutting	Rock with low UCS and low abrasivity (e.g. shale, weak sandstone, phyllite)

Thuro (1997)

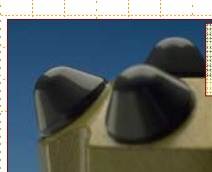
Drill & Blast – Drill Bit Buttons

The bit's ability to penetrate the rock efficiently depends on the contact surface of the buttons, their shape and number, the bits' flushing characteristics and the brittleness, or drillability, of the rock.





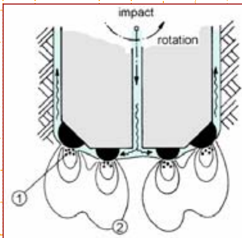
Thuro (1997)



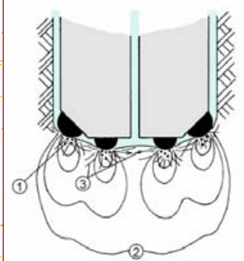
9 x 45 b = 9 buttons, ∅ 45 mm, and b – ballistic.

8 x 45 s = 8 buttons, ∅ 45 mm, and s – spherical.

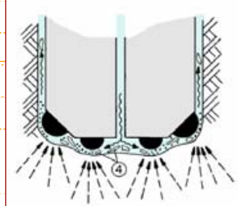
Drill & Blast – Drill Bit Buttons



1. ***Begin of impact:*** Rotating hard metal buttons are forced into the rock mass. Extremely high local stresses cause the prompt formation of crushed zones ① below the tips. From there, low level stress fields ② are built up in the drilling direction.



2. ***Cracking:*** The rising stresses exceed the rock strength, initial cracks ③ form at the edge of the crushed zones and propagate into the rock. Cracks from neighbouring zones begin to interact and form chips. Shearing takes place due to bit

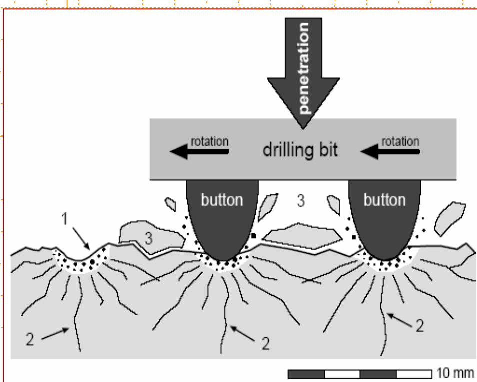


3. ***End of stroke:*** The bit is pulled back, the stresses are released. Elastic rebound of the rock mass and the flushing system separate chips and crushed material ④ from the front. They are flushed out of the hole consequently.

Plinninger et al. (2002)

Drill & Blast – Drill Bit Buttons

Around the contact of the button a new state of stress is induced in the rock, where four important destruction mechanisms can be distinguished:

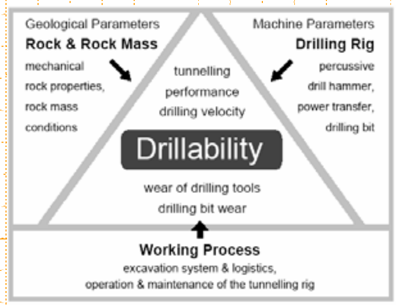


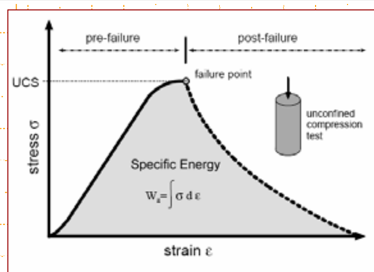
1 crushed rock powder 2 radial cracks 3 detached fragments

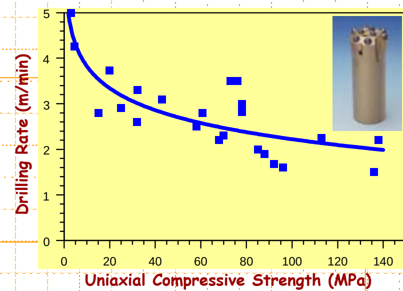
Thuro (1997)

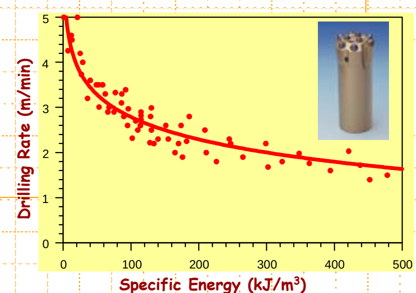
1) Under the bit button a crushed zone of fine rock powder is formed (impact).
2) Starting from the crushed powder zone, radial cracks are developed (induced tensile stress).
3) When stress in the rock is high enough (if enough cracks exist ± parallel to the bottom of the borehole), larger fragments of the rock can be sheared off between the button grooves (shear stress).
4) In addition to the mechanisms above stress is induced periodically (dynamic process).

Drill & Blast – Drilling Rates



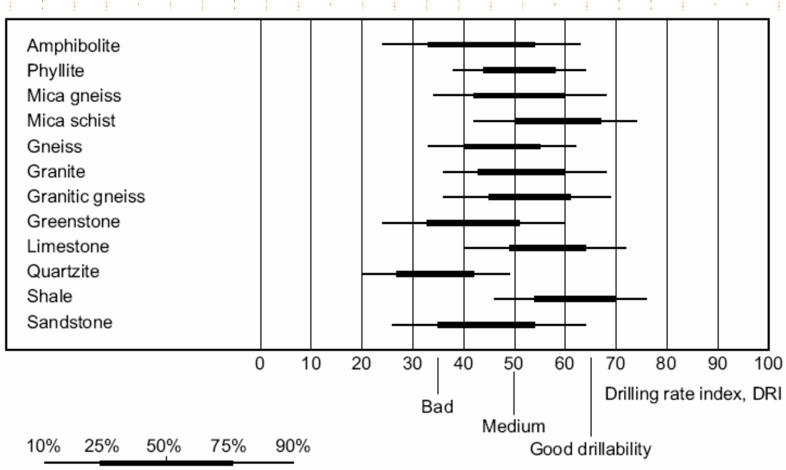






Thuro (1997)

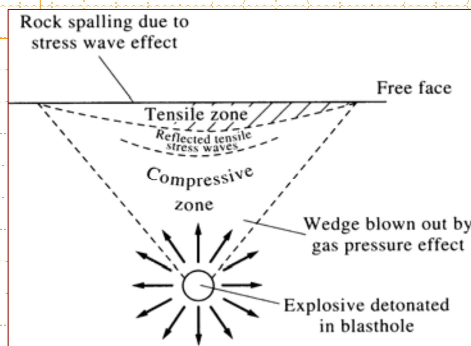
Drill & Blast – Drilling Rates



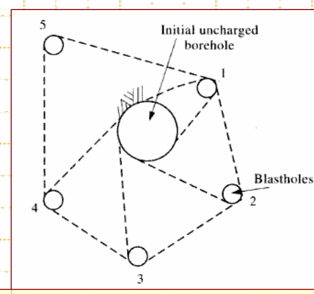
UNIT-NTH (1995)

Blasting Rounds – Blast Pattern Design

One of the basic principles of designing the configuration and sequential detonation of blastholes in a one blast, is the presence of a free face parallel or sub-parallel to the blast holes, as detonation occurs. In some cases, these free faces may already be present (benches in an open pit mine), but in other cases may need to be created by the blast itself (a tunnel face).



Hudson & Harrison (1997)



Practical application of the free-face concept using one form of the burn cut.

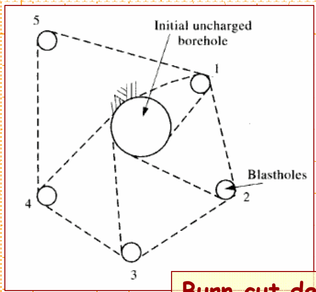
Blasting Rounds – Blast Pattern Design

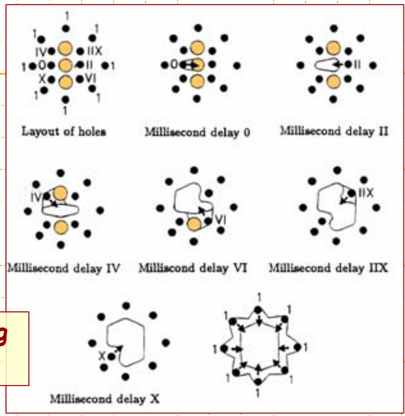

Blast along free-face.


Partially confined blast.

Blasting Rounds – Burn Cut

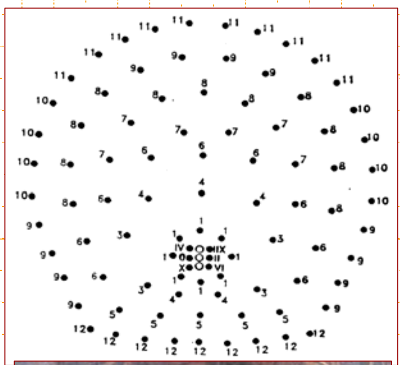
The correct design of a blast starts with the first hole to be detonated. In the case of a tunnel blast, the first requirement is to create a void into which rock broken by the blast can expand. This is generally achieved by a wedge or burn cut which is designed to create a clean void and to eject the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

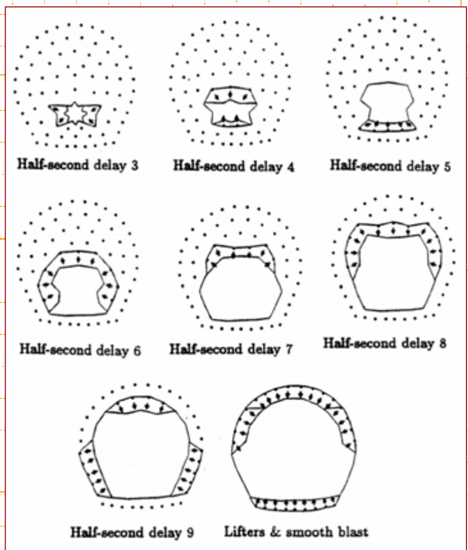




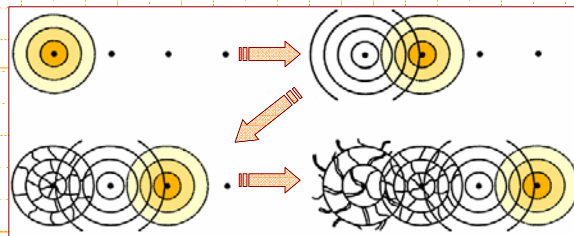
Burn cut designs using millisecond delays.

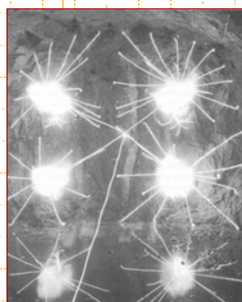
Blasting Rounds – Blast Pattern Design

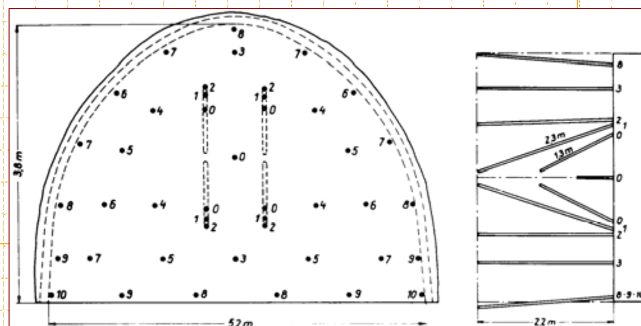




Blasting Rounds – Blast Pattern Design

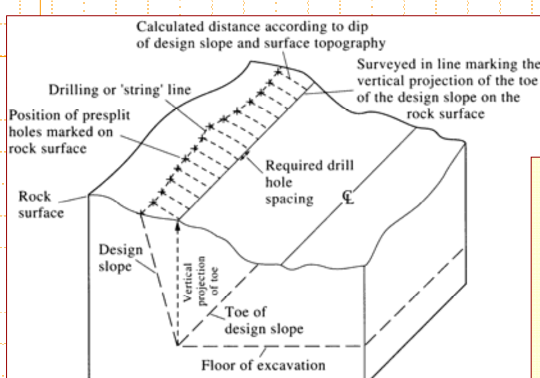






Specialized Blasting Techniques

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 pre-split blast (surface excavation) or smooth-wall blast (underground) may be used to create the final excavation surface.

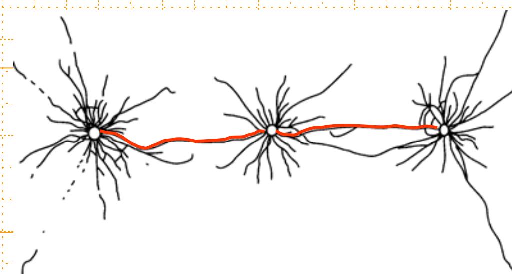


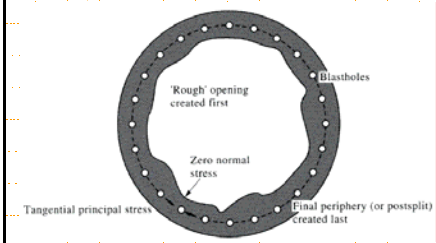
Hudson & Harrison (1997)

Pre-split blast: First a series of small-diameter, parallel boreholes are drilled along the plane of the required final excavation boundary (i.e. rock cut slope).

Pre-Split & Smooth-Wall Blasting

The principle is then to tailor the explosive parameters such that detonation of the explosives in these initial holes will primarily create a plane of intersecting holes through the coalescence of several induced fractures.



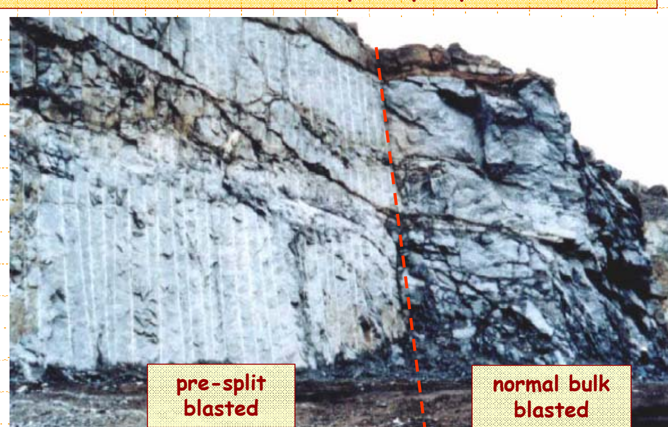


Hudson & Harrison (1997)

The smooth-wall blast follows a similar process to the pre-split blast, except in the reverse order. First a rough opening is formed using a large bulk blast, and then the smooth-wall blast follows along a series of closely spaced and lightly charged parallel holes.

Pre-Split Blasting

When, subsequently, the main body of rock is blasted to form the cutting, the pre-split reflects the stress waves back into the rock being excavated and dissipates excess gas pressure, such that the bulk blast has little effect of the rock behind the pre-split plane.



Blasting Rounds - Explosives

Commercial explosives are mixtures of chemical compounds in solid or liquid form. Detonation transforms the compounds into other products, mostly gaseous.

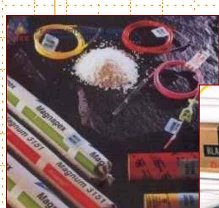
The following are the main criteria applied to select an explosive for a given type of blasting:

- available energy per unit weight of explosive (i.e. strength)
- density of the explosive
- detonation velocity
- sensitivity (ease of ignition)
- reaction rate
- temperature and pressure
- stability (chemical and storage)

Blasting Rounds - Explosives

The following are the more common explosives used in hard rock excavation:

- dynamites (nitroglycerin made stable by dissolving it in an inert bulking agent – moderate bulk strength)
- ANFO (Ammonium Nitrate & diesel Fuel Oil – low bulk strength)
- slurries (water gels – high bulk strength for wet conditions)
- emulsions



ANFO is the most prevalent explosive used in mining because it is the least expensive and the safest to transport and handle. ANFO type explosives are susceptible to water and, therefore, are not suitable for wet blastholes.

Blasting Rounds - Explosives

Low explosives, like black powder, can be fired by the flame from a fuse or a match. High explosives require stronger ignition, usually a powerful high temperature shock from a substance that detonates at a very high rate. Some of these devices include:

- Blasting caps
- Squibs/Delays
- Safety fuse
- Primacord

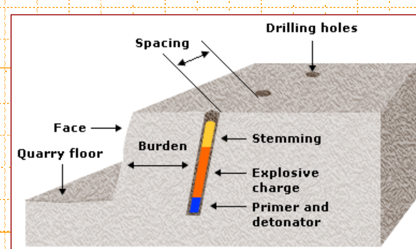
Delays: used to orchestrate rotational firing.

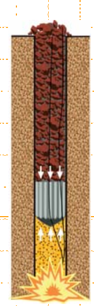
Primacord: ignition velocity is approx. 6,400 m/s.

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

Blasting Rounds - Stemming

"Stemming" materials (e.g. pea-sized gravel), are used to top-off the blastholes. The stemming material acts to provide confinement, preventing the explosive gases and energy from travelling (venting) up through the drill hole, and instead are contained within the rock mass.





Blasting Rounds – Blasting Caps

Blasting caps come in a variety of forms. Electric detonators consist of an aluminum tube with an electrically activated fusehead which initiates a priming charge and then a base charge of high explosive.

Fuse caps are non-electric blasting caps that use primary explosives such as mercury fulminate (very sensitive) or lead azide (in copper shells) to provide a quick heat source. They come in small metal tubes (3-5 cm long), closed on one end and open on the other to accept the end of a safety fuse.

Except for the means of firing, there is little difference between electric and fuse-type blasting caps.

Word to the wise: Do not crimp fuse-type blasting caps to fuses using your teeth.

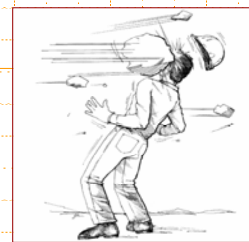
Blasting Rounds – Delays

Delay, or rotational, shooting has many advantages over instantaneous firing in almost all types of blasting. It generally gives better fragmentation, more efficient use of the explosive, reduced vibration and concussion, and better control of the rock. For these, and sometimes other reasons, most blasting operations are now conducted with a delay system. Generally, delay detonators are produced as either 'short delay', measured in milliseconds, or 'half-second delay', measured in seconds .

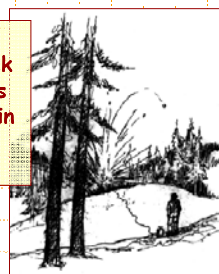
Blasting Rounds – Fly Rock

Fly rock is a constant concern to blasters and their co-workers. It can be controlled if proper preparation, blasting techniques and safety procedures are followed. Four of the major causes of excessive fly rock are:

- Geology conditions.
- Inaccurate drilling and loading.
- Poor hole design.
- Poor pattern timing.



Incidents have been recorded where flyrock has travelled in excess of 1 km and resulted in significant damage, injury and/or death.



Blasting Rounds – Fragmentation

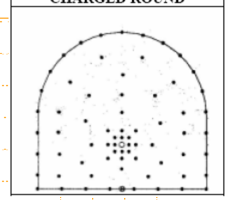
How efficiently muck from a working tunnel or surface excavation can be removed is a function of the blast fragmentation. Broken rock by volume is usually 50% greater than the *in situ* material. In mining, both the ore and waste has to be moved to surface for milling or disposal. Some waste material 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

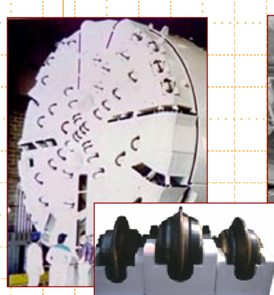


Typical production round fires in less than 7 seconds

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

NTNU (1995)

Mechanical Excavation



Mechanical Excavation

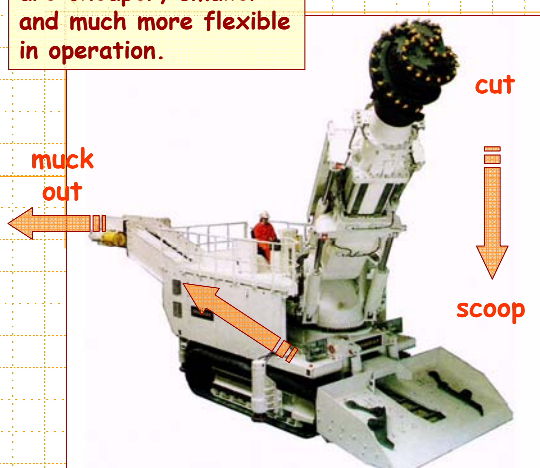
There are two basic types of machine for underground excavation: partial- and full-face machines:

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

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

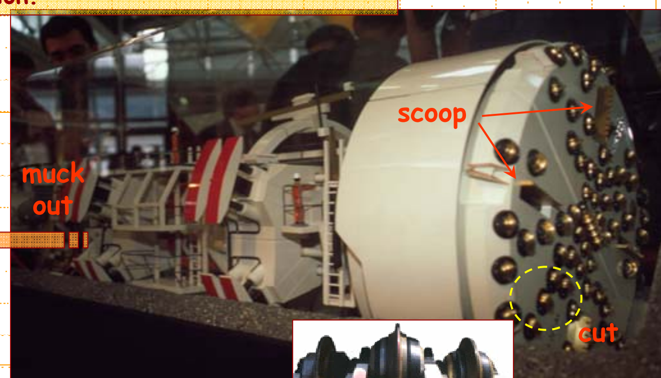
Mechanical Excavation

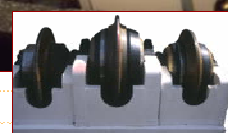
Partial-face machines are cheaper, smaller and much more flexible in operation.



Mechanical Excavation

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.

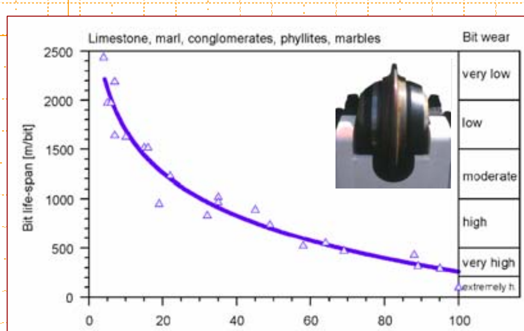
The cutters may jam if the TBM is pushed forwards with too much force. Then they might scrape against the rock and become flattened on one side.

Mechanical Excavation – Tool Wear

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

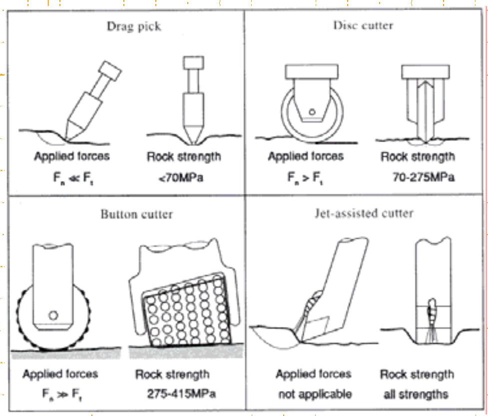
Mechanics of Rock Cutting – Tool Wear

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.



Mechanics of Rock Cutting

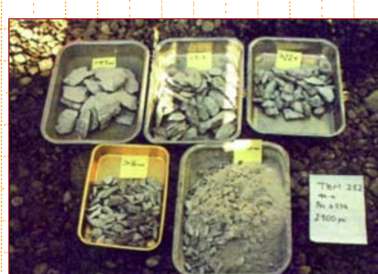
In tunnelling terms, a TBM applies both thrust (F_n) and torque (F_t) during the cutting process. In selecting the proper cutting tool, the engineer wishes to know how the tools should be configured on a machine cutting head, how to minimize the need to replace cutters, how to avoid damaging the cutter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

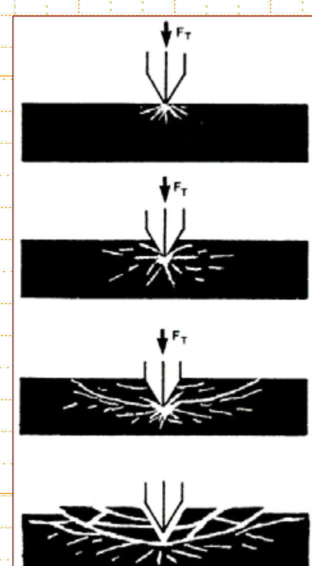


Hudson & Harrison (1997)

Mechanics of Rock Cutting – Disc Cutter

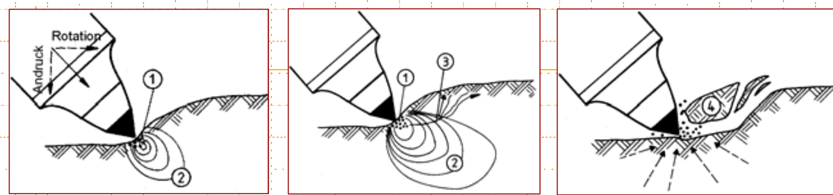
The mode of cutting involves a complex mixture of tensile, shear and compressive modes of failure. With thrust, the cutting disc penetrates the rock and generates extensive crack propagation to the free surface. Further strain relief occurs as the disc edge rolls out of its cut, inducing further tensile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



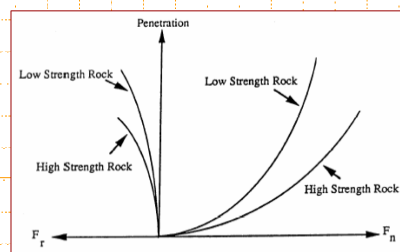


Whittaker & Frith (1990)

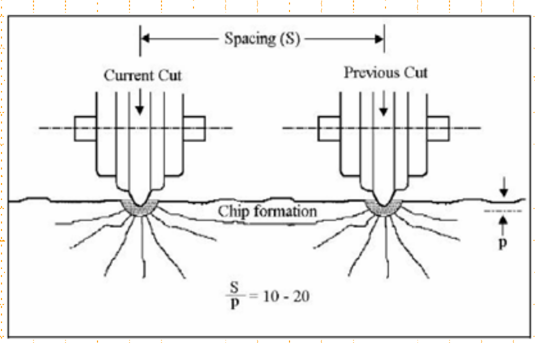
Mechanics of Rock Cutting – Drag Pick

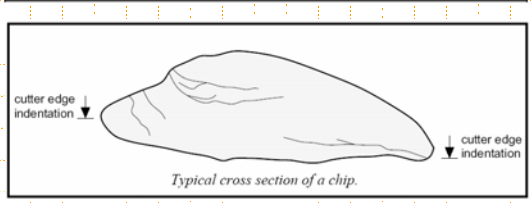


1. Force applied causing zone of surface crushing
3. Initiation and propagtaion of microfractures
4. Breaking and ejection of rock chip
2. Induced stresses from point load

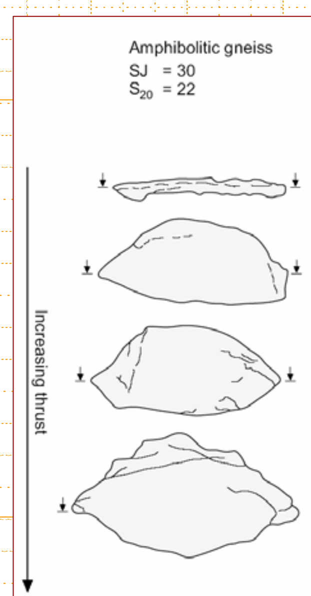


Mechanics of Rock Cutting





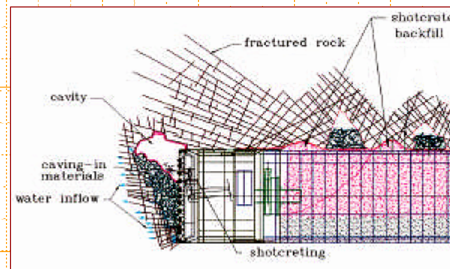
Typical cross section of a chip.

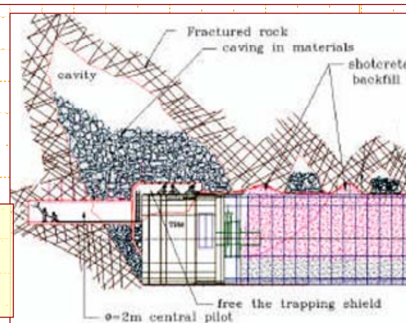


NTNU-Anleggsdrift (1998)

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

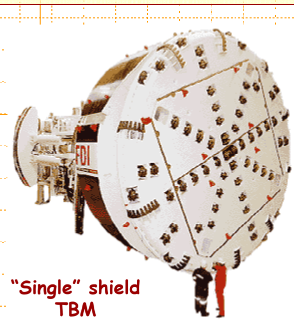
Table 1 : General classification scheme for tunnelling machines (AITES / ITA, Working Group No.14).

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

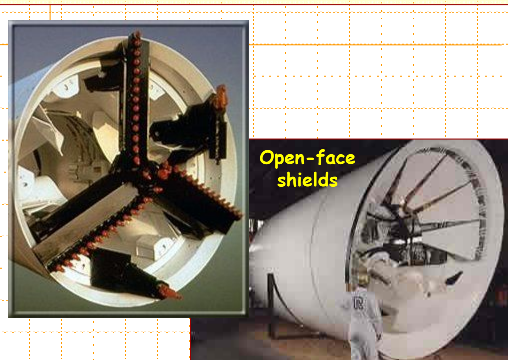


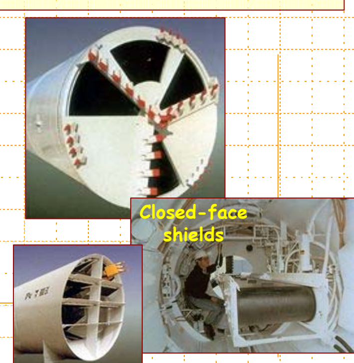
"Single" shield TBM

"Double" shield TBM

TBM Excavation & Design

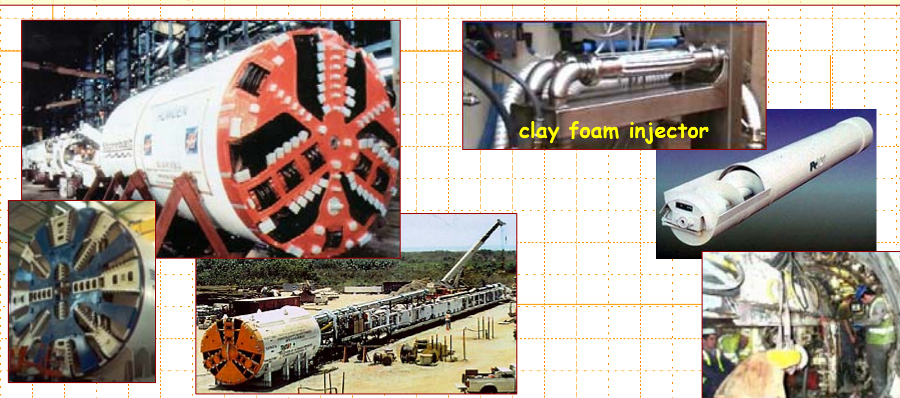
Open- & Closed-Face Shields – When the tunnel face does not require a continuous and pressure balanced support, the TBM is operated in 'Open Mode'. The face is mechanically supported by the cuttinghead while the flood control doors regulate muck flow from the face to the cuttinghead chamber. The excavated muck is rapidly extracted by the conveyor. With a closed-face, an airlock and bulkhead are used to allow the "excavation chamber" to be pressurized with compressed air to aid face support.





TBM Excavation & Design

Earth Pressure Balance (Closed-Face Shield) – This method provides continuous support to the tunnel face by balancing earth pressure against machine thrust. As the cutterhead rotates and the shield advances, the excavated earth is mixed with foams in the cutterhead chamber to control its viscosity. The pressure is then adjusted by means of the rate of its extraction (by screw conveyor) to balance the pressure exerted by the ground at the tunnel face. This enables near surface tunnelling in bad ground conditions with minimal surface settlement.



TBM Excavation & Design

Impacts of Geotechnical Conditions on TBM Operations

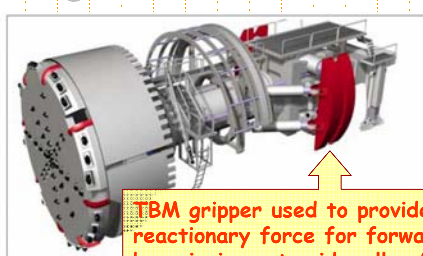
Major Geotechnical Conditions	Consequences/Requirements
Loosening loads, blocky/slabby rock, overbreak, cave-ins	At the face: cutterhead jams, disc impact loading, cutter disc and mount damage possible, additional loss on available torque for cutting, entry to the face may be required with impact on 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.

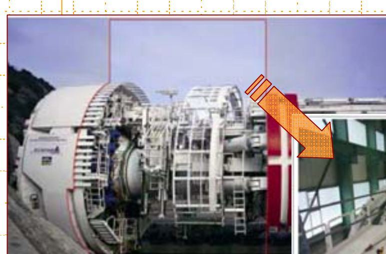
TBM Excavation & Design

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.

TBM Excavation & Design

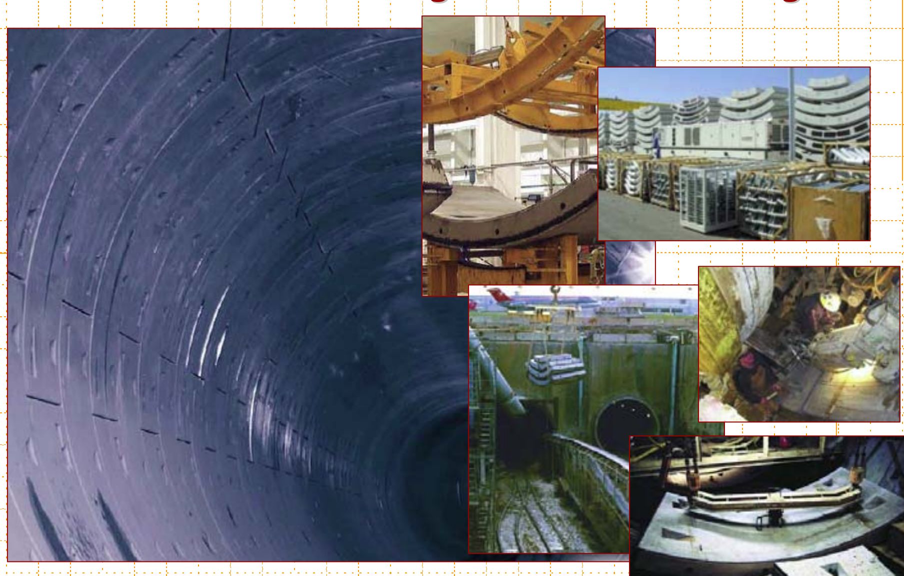




TBM Excavation & Design - Benches

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.

TBM Excavation & Design - Pre-Cast Linings



Tunnelling Breakthroughs