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.

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/m³). 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.

Conventional Drill & Blast Cycle

Diagram showing the steps of the conventional drill & blast cycle: drill, load, blast, ventilate, bolt, scoop, and scale.
Drill & Blast – Drilling Rates

- Geologic Parameters
  - Rock & Rock Mass
  - Mechanical properties
  - Rock mass conditions
- Drillability
  - Wear of drilling tools
  - Drilling bit wear

- Working Process
  - Excavation system & logistics
  - Operation & maintenance of the drilling rig

Drilling Rate (m/min)

Uniaxial Compressive Strength (MPa)

Specific Energy (kJ/m³)

Drill & Blast – Drilling Rates

<table>
<thead>
<tr>
<th>Geologic Parameters</th>
<th>Machine Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock &amp; Rock Mass</td>
<td>Drilling Rig</td>
</tr>
<tr>
<td>Mechanical</td>
<td>岩石特性</td>
</tr>
<tr>
<td>Properties</td>
<td>岩体条件</td>
</tr>
<tr>
<td>Drillability</td>
<td></td>
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<tr>
<td>Wear of tools</td>
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<tr>
<td>Drilling bit wear</td>
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</tr>
</tbody>
</table>


- Amphibolite
- Phyllite
- Mica gneiss
- Mica schist
- Gneiss
- Granite
- Granitic gneiss
- Greenstone
- Limestone
- Quartzite
- Shale
- Sandstone

Drilling rate index, DRI

- Bad
- Medium
- Good drillability

10% 25% 50% 75% 90%
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.

Blast Pattern Design

Burn cut designs using millisecond delays.

Blasting Rounds – Blast Pattern Design

Half-second delay 3
Half-second delay 4
Half-second delay 5
Half-second delay 6
Half-second delay 7
Half-second delay 8
Half-second delay 9
Lifters & smooth blast
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.

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

<table>
<thead>
<tr>
<th>CONTROLLABLE VARIABLES</th>
<th>CHARGING</th>
<th>BLASTING</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DRILLING</strong></td>
<td>Diameter drill hole</td>
<td>Type of explosives</td>
</tr>
<tr>
<td></td>
<td>Drilled length</td>
<td>Energy of explosives</td>
</tr>
<tr>
<td></td>
<td>Drill pattern</td>
<td>Charging method</td>
</tr>
<tr>
<td></td>
<td>Incorrect drilling</td>
<td>Design of charging</td>
</tr>
<tr>
<td><strong>NON-CONTROLABLE VARIABLES</strong></td>
<td><strong>GEOLOGY</strong></td>
<td><strong>OTHER</strong></td>
</tr>
<tr>
<td></td>
<td>Rock parameters</td>
<td>Incline/Decline</td>
</tr>
<tr>
<td></td>
<td>Rock mass part</td>
<td>Water (purity)</td>
</tr>
</tbody>
</table>

CHARGED ROUND

RESULT

- Fragmentation
- Threw
- Mist pile shape
- Loadability
- Vibrations
- Advance per round
- Contour
- Flyrock
- Non-detonating holes
- Poor blast result

Typical production round fires in less than 5 seconds.
There are two basic types of machine for underground rock excavation:

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

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.

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 ($F_t$) and torque ($F_q$) 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.

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.
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
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.

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

<table>
<thead>
<tr>
<th>Location</th>
<th>Method</th>
<th>Tool</th>
<th>Rock/Mortar</th>
<th>Category</th>
<th>Type</th>
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<tbody>
<tr>
<td>None</td>
<td>Cutting disk</td>
<td>Grizzlies</td>
<td>Full Face Boring Cutting Head (FBC)</td>
<td>Rock Deformation</td>
<td>Single Shielded TBM (SS-TBM)</td>
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<tr>
<td>None</td>
<td>Cutting box</td>
<td>Shear Jaws</td>
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<td>None</td>
<td>End header/back lobe</td>
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<tr>
<td>None</td>
<td>Cutting bits</td>
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</table>
TBM Excavation & Design

Single & Double Shield TBMs - Single-shield TBMs are cheaper and are the preferred machine for hard rock tunneling. 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

<table>
<thead>
<tr>
<th>Major Geotechnical Conditions</th>
<th>Consequences/Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose/weak, blocky/instable rock, overbreak, cave-ins</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td>In the tunnel: short stand-up time, delays for immediate and additional support (perhaps greaser, hand-mining), special equipment (perhaps machine modifications), grout anchorage and steering difficulty, shut-down in extreme cases of face and crown instability. Extent of zones (perhaps with verification by advance sensing/drill 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.</td>
</tr>
<tr>
<td>Groundwater inflow</td>
<td>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/drill hole drilling. Corrosive or high-salts 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.</td>
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</table>

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TBM Excavation & Design

Impacts of Geotechnical Conditions on TBM Operations

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<td>Squeezing ground</td>
<td>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.</td>
</tr>
<tr>
<td>Ground gas/hazardous fluids/wastes</td>
<td>Construction safety concerns, safe equipment more expensive, need increased ventilation capacity, delays for advance sensing/plotting and perhaps project shut-down, special equipment modifications with great delays if unanticipated, muck management and disposal problems.</td>
</tr>
<tr>
<td>Overstress, spills, bursts</td>
<td>Delays for immediate support, perhaps progress shut down, construction safety concerns, special procedures may be required.</td>
</tr>
<tr>
<td>Hard, abrasive rock</td>
<td>Reduced PPRev and increased Pp, 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.</td>
</tr>
<tr>
<td>Mixed-strength rock</td>
<td>Impact disc loading may increase failure rates, concern for side wall gripping problems with open shales, possible slaming problems.</td>
</tr>
<tr>
<td>Variable weathering, soil-ike zones, faults</td>
<td>Slowed progress, if sidewall grippers not usable may need shield, immediate and additional support, potential for groundwater inflow, muck transport (handling and disposal) problems, sawing difficulty, weathering particularly important in argilaceous rock.</td>
</tr>
<tr>
<td>Weak rock at invert</td>
<td>Reduced utilization from poor traffickability, grade, and alignment - sawing problems.</td>
</tr>
</tbody>
</table>

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.

1980s: 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.
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


