TUNNELLING IN ROCKS – PRESENT TECHNOLOGY AND FUTURE CHALLENGES

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Introduction: Rock Tunnelling

Rock tunnelling involves:
   Rock excavation – to make a hole.
   Rock support – to sustain the hole.

Rock Excavation:
   Excavation technology is primarily driven by rock excavation machine technology.

Rock Support:
   Support technology is largely driven by rock mechanics science together with support material technology.
Introduction: Rock Tunnel History

Canal du Midi (Languedoc) tunnel (1666-81), first use of explosive (black powder).

Hoosac tunnel (1851-75), first of use of dynamite (invented in 1860s). Also the first attempt of a tunnel boring machine (TBM).

Mont Cenis (Fréjus) tunnel (1857-71), used compressed air drill, made 5 m/day advance rate.

Gotthard tunnel (1872-1880), the longest (15 km) then.

Simplon tunnel (1898-1906), for years (until 1982) as the longest tunnel, 19.8 km.
Introduction: Rock Tunnel History

Start of rock TBM (1951), at the Oahe Dam (shale) and later at the Humber Sewer (hard rock) tunnels.

Seikan tunnel (1972-88), 54 km long with undersea length of 23 km.


Channel tunnel (1994), 52 km long with longest undersea length of 39 km, by TBMs.

Gotthard base tunnel, longest tunnel (57 km), with maximum overburden of 2.4 km, 90% by TBM.

Niagara tunnel, with largest rock TBM, ø14.4 m.
Modern rock tunnels are excavated by primarily two methods:

Drill-and-Blast (D&B): It involves drilling charge holes advancing into rocks and using explosives to blast the rocks.

Tunnel Boring Machine (TBM): It involves cutting rock by a full face boring machines. Tunnelling machines for partial face (roadheader) are also used for rock excavation.
Rock Excavation: Drill-and-Blast

Drilling

Charging

Survey

Blasting

Bolt

Ventilation

Shotcrete

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

Since 1945, tungsten carbide drilling bits have been used.

In 1960s, pneumatic drilling was introduced.

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

Since 1980s, computer aided rock drilling started.
Drilling performance increased from 5 m/hour 100 years ago to 450 m/hour today.
Rock Excavation: Blasting Technology

Before 1860s, black powder was used.

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

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

1955, ANFO (ammonium nitrate fuel oil) introduced.

In 1960s, water gel and slurries.

In 1970s, non-electric initiation developed.

In 1980s, emulsion explosive developed and used in tunnelling since 1990s.
Emulsion explosives are water resistant, safe and pumpable, and produce less toxic gases.

Charging blast holes with emulsion explosives to excavate the Singapore Underground Ammunition Facility (UAF) storage caverns.
Computerized and automated hydraulic drilling jumbos are widely used. Drilling plans are stored in computer, precise positioning and navigation are by laser. Excavated profiles can be scanned for guiding next drilling and blasting.

In Lötschberg base tunnel (section about 70 m²), over 6 m/day average progress for 4.6 km in granite, gneiss, schist and limestone, with maximum 16 m/day in granite.
Computerised 3-boom drilling jumbos used in Singapore UAF caverns

Computerized and automated hydraulic drilling jumbo, with drill plan stored in computer. No marks on the face.
Emulsion explosives combined with non-electric initiation system are used to provide a safer and more efficient tunnelling operation. Quantity of pumpable emulsion can be controlled by computerized system.

Emulsion explosives were use to blast this and other granite caverns in Singapore (1999-2002). Emulsion explosive were stored on site.
Rock Excavation: D&B Today

Full large face excavation, even in poor rock mass, with face auxiliary methods.

Various face auxiliary methods have been developed, including forepole umbrella, fibreglass reinforcement.
Tunnel Boring Machine (TBM) is an excavation machine cutting the rock full face by pushing and rotating the cutterhead. Tunnel support is done behind.
Rock Excavation: TBM Technology

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

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

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

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

In 1960s, roadheader was introduced to tunnelling.
Rock Excavation: TBM Technology

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

Niagara tunnel, with largest TBM, ø14.4 m.
Rock Excavation: TBM Technology

Development of TBM Cutterhead

Cutter diameter (mm):

Maximum cutter force (kN/cutter):

Cutterhead rotation speed (RPM);

TBM in Switzerland

• 1965, first TBM (Ø3.5 m)
• 1979, Gubristtunnel (Ø11.52 m)
• In 1970s, 83 km road and railway tunnels
• 1985 – 1999, 17 large scale TBM used
• largest diameter: Adlertunnel Ø12.58 m
Rock Excavation: TBM Technology

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

Convertible EPB–slurry TBM for poor rock and mixed ground
Rock Support

Rock tunnel support are divided into two categories:

Temporally support: This is a short-term measure only to provide a safe working environment for continuous excavation. Common techniques are bolts and shotcrete.

Permanent support: This is long-term support for a life-span of the tunnel. The methods available are steel set, cast-in concrete, concrete segment, bolt, shotcrete (with or without steel fibre reinforcement).
Two main rock support systems: bolt and shotcrete (left, for D&B and TBM tunnels) and concrete segment (right, for TBM tunnels).
1942, based on rail tunnel experiences in the Alps, Terzaghi introduced Rock Load Factor, first time classified rock into 9 behaviour classes, ranging from solid massive to squeezing and swelling. It allows to estimate the total load that the steel arch need to design for.
1960-70s, Ground-support interaction and observation based support design concept introduced. It allows ground deformation and stress redistribution, to optimise the support applied to the rock, by taking the rock-support interaction into account.
1970s, Rock mass quality classifications (RMR and Q) introduced as tools for rock mass quality assessment and basis for rock support design.
Since 1980s numerical modelling methods were used for analysis and design. Notably, discrete element method (DEM) was applied to model discontinuous rock masses.

DEM modelling on support design and stability analysis for the 61 m span cavern in Gjovik, Norway.
1980s, Hoek-Brown strength criterion was developed, and was improved with the introduction of Geological Strength Index (GSI) in 1990s.

It is the most widely used criterion to estimate rock mass strength, and to provide rock mass parameters for design.
Before 1950s, steel arch is the main support method.

In 1920s, rock bolts were tried and became widely used since 1950s, seeing the development of expansion shell anchor.

1970s, split set, and 1980s, Swellex was introduced.
1950s, dry-mix and 1960s wet-mix sprayed concrete introduced, and since 1980s, wet-mix became widely applied.

1970s, steel fibre reinforced sprayed concrete (SFRS) was experimented and in 1980s it gained wide applications.
Rock Support: Support Design Today

Support design based on rock mass quality classifications, mainly, RMR and Q, mostly for competent rock masses.

Support design and implementation based on sequential excavation and observation, particularly for poor ground.

Physical and numerical modelling for non-precedent or special cases.
Support design criteria coupling analysis, modelling and in situ measurement, i.e., integrated design.

Prediction of squeezing combining strength criterion and numerical modelling, for different rock mass strength to in situ stress ratios (Hoek 2000)
A wide selection of end-anchored, frictional, and fully grouted rock bolts are available.

For quick initial support, both in D&B and gripper TBM tunnelling, anchored and frictional bolts are used.

To combine initial and permanent support, anchored bolts are used and followed by full grouting.

Initial support by bolts, wire mesh and shotcrete at Lötschberg base tunnel.
Wet-mix sprayed concrete is the main method, and often with steel fibre reinforcement (SFR). Additives can be added to improve concrete performance, mainly to gain strength faster.

This 30 m span cavern was supported typically by fully grouted spot anchor bolts, and SFRS concrete. UAF caverns in granite, Singapore (1999-2002).
Challenges and Future Development

Tunnelling also faces much great challenges due to geological and environmental constrains. Tunnels have to be built for large size in dense urban areas, under great depth below mountains, across deep rivers and seas. Tunnels also have to be operated safely for massive transportation, and ensure the safety under unusually circumstances such as terrorism. To large extent, the challenges to build and operate tunnels safely in modern environments have to be met by technology innovations, with research and development, training and technical exchange.

-- Jian Zhao, World Tunnel Congress 2004, Chairman’s Welcome Message
Challenges and Future Development

European Vision of Underground Construction in 2030

“Free above ground space for the use of the citizens, taking infrastructures underground.”

“Underground construction will be safe and with no impact on the environment.”

--European Construction Technology Platform, 2006
Challenges and Future Development

Tunnelling Activities in Europe by 2030:
- 2100 km new tunnel,
- Over 500 tunnels to be refurbished,
- Tunnelling a major European industry, involving 450,000 people.

Tunnelling in China by 2010:
- 300 km for rail,
- 150 km for road,
- 100 km for metro.

This 32 km tunnel on Qinghai-Tibet rail line is to be constructed within 3 years (by 2010) by TBM and D&B, in some poor rocks and with 1100 m overburden.
Challenges and Future Development

European Vision of Underground Construction 2030 Break-through:

2010 – Self learning equipment (equipment making automatic modification during construction);
Cost efficient large diameter tunnels;
Intelligent lining system (automatic modification of lining with ground condition).

2020 – Breakthrough in rock cutting technology (e.g., laser cutting);
Complete knowledge of geological conditions (transparent ground);
Universal tunnel boring machine.
Challenges and Future Development

European Vision of Underground Construction 2030 Break-through:

2030 – No environmental impact (complete waste reuse and no air and water pollution);
Complete knowledge of underground facilities behaviour;
Similar cost for underground and above ground infrastructures;
No workers inside tunnel during construction (totally automated remotely controlled tunnel construction work).
Future R&D: Excavation Machine

Full automation of drilling jumbo and remote control.

Laser and other new rock cutting technologies.

Invention of pollution-free explosives.

TBM to increase net penetration rate and cutter life in very hard and abrasive rocks.

TBM able to excavate through complex and variable geology, i.e., universal TBM.
Future R&D: Rock-Machine Interaction

A rock mass classification scheme, incorporating appropriate rock mass properties for TBM excavation;

A TBM performance prediction model for various rock and complex geology;

A guide for TBM operation in complex ground.
Future R&D: Rock Support Mechanics

Short and long term behaviour of complex grounds, e.g., squeezing and spalling.

Effects of changing ground condition and environment on the durability and long term stability of tunnels.

Support mechanism of large opening, the effectiveness of bolts.

Rock support mechanism and method for tunnel under dynamic loads.
Future R&D: Underground Space
Safety and Environment

Fire and safety in underground facilities.

Environmental integration during underground construction.

Architecture and environment in underground space utilisation.

Proposed Underground Science City, Singapore

Laboratoire de Mécanique des Roches – LMR
Examples of Challenges: Unforeseen Ground Conditions?

How much site investigation is required in order to minimize “unforeseen” ground conditions in tunnelling?

(Data given by Hoek)
Examples of Challenges: Empirical or Numerical Design?

Case example, minimum rock separation between two near parallel tunnels, UAF Project, Singapore

Original empirical design: 15 m
Optimised by numerical modelling: 8 m
Considering rock mass properties, stress conditions, effects of rock reinforcement, and construction method/sequence.

Construction implication: saved 200 m tunnelling in granite.
Examples of Challenges:
TBM in Blocky and Faulted Rocks

TBMs have difficult to progress through highly fractured rock mass, faulted zones, mixed ground, squeezing and spalling rocks. A re-examine of TBM fragmentation mechanism is needed.
Examples of Challenges:
TBM in Rock-Soil Mixed Ground

TBMs in mixed ground and rock-soil interface are having low advance rate, low utilization, and excessively high cutter damage and wear.

Improved knowledge on excavation mechanism in complex ground is needed.
Examples of Challenges:
Rock Self-Support Mechanism

<table>
<thead>
<tr>
<th>Rock Conditions &amp; Bolt Parameters</th>
<th>Gjovik Cavern, Norway (Based on Broch et al. 1996)</th>
<th>UAF Cavern, Singapore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Rock Mass Quality</td>
<td>1~30</td>
<td>4~36</td>
</tr>
<tr>
<td>Vertical Stress, MPa</td>
<td>1</td>
<td>2~3</td>
</tr>
<tr>
<td>Maximum Horizontal Stress</td>
<td>3.5</td>
<td>8.2</td>
</tr>
<tr>
<td>Minimum Horizontal Stress</td>
<td>2</td>
<td>4.6</td>
</tr>
<tr>
<td>Ratio of Horizontal to Vertical Stress</td>
<td>2~3.5</td>
<td>2~3</td>
</tr>
<tr>
<td>Tunnel/cavern span, meters</td>
<td>61</td>
<td>30</td>
</tr>
<tr>
<td>Type of Rock Bolts</td>
<td>Fully grouted rebars</td>
<td>Fully grouted bolts</td>
</tr>
<tr>
<td>Bolt lengths</td>
<td>6 (with alternating 12 m long cables)</td>
<td>5</td>
</tr>
<tr>
<td>Spacing, meters</td>
<td>2.5 x 2.5</td>
<td>1.5~2.4</td>
</tr>
<tr>
<td>Bolt Capacity, KN</td>
<td>220</td>
<td>250</td>
</tr>
<tr>
<td>Minimum Measured Loads, KN</td>
<td>1~1.5</td>
<td>3~12</td>
</tr>
<tr>
<td>Typical Measured Loads, KN</td>
<td>30~60</td>
<td>20~60</td>
</tr>
<tr>
<td>Typical Load Percentage</td>
<td>13~27%</td>
<td>8~24%</td>
</tr>
<tr>
<td>Maximum Measured Load, KN</td>
<td>87</td>
<td>70</td>
</tr>
<tr>
<td>Max Load Percentage</td>
<td>40%</td>
<td>28%</td>
</tr>
</tbody>
</table>

Low load on bolts suggests rock is self-supporting.

How effective are bolt and shotcrete in rock support?
Examples of Challenges:

Squeezing and Weak/Poor Rocks

Although known as a stress induced problem, it is still difficult to predict and to quantify deformation and load inserted on lining, for tunnels in squeezing and weak/poor rock masses.

1.5 m of displacement in a fault zone in the 16 m span Mucha highway tunnel in Taiwan
Examples of Challenges:
Earthquake and Explosion

How does dynamic stress wave propagate in rock mass?
How do rock mass and support respond to dynamic loads?
How to design tunnels subjected to dynamic loads?

Safe separation distance between caverns?
Examples of Challenges:

Durability and Long-Term Stability

Cracking in some old road tunnel linings in Switzerland

To understand the effects of time and environment change on rock and support, and to be able to quantify structural degradation and damage.
Tunnelling in Rock: Continuing Battles

Tunnelling is fighting through the ground.

We certainly need good weapons (machines and materials). More importantly we need to know enemy (ground): what are they, and how do they respond when under attack (construction)?

To win the complete battle, we must know the ground before, during and after tunnelling, i.e., in situ properties of rock, and the mechanics of rock-construction-environment interaction.

Thank You!