Pressurised TBMs and their interaction with weathered rock

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Pressurised TBMs

- Two basic types: slurry or Earth Pressure Balance (EPB)
- Fundamental differences in how they provide pressure to support the face
- Some modern TBMs can change from Slurry to EPB, including the ‘variable density’ TBM
Pressurised slurry
Application of slurry pressure

Membrane model
- Slurry
- Soil
- Filter cake formed

Penetration model
- Slurry
- Soil
- Pure penetration

Materials:
- Fine sand
- Medium sand
- Coarse sand
- Gravel
Earth Pressure Balance

Pressurised spoil

Increase / Reduction of Shield Advance Rate

Increase / Reduction of Screw Discharge Rate

Water Pressure

Earth Pressure
Screw Conveyor

Excavation Chamber – face pressure

Discharge – at atmospheric pressure

Pressure drop along screw conveyor = difference between face pressure and atmospheric
EBP-Shield Taipai (Ø 6.26 m), belt conveyor outlet

Ideal soil for EPB operation – low permeability & plastic, to support pressure drop along screw conveyor
Typical mixed ground cutterhead

Discs for rock and scrapers for soil

Opening ratio 25% to 35% (example is 33%)
Interventions

Confined space to:
- Inspect and change cutting tools
- Tighten bolts
- Repair grizzly bars, mixing and crusher arms
- Remove blockages, lost steel
Interventions

Typically under compressed air in soil & mixed ground
Damage in mixed faces of rock and soil

Impact damage to discs

Abrasion

Damage to mixing and rock crusher arms, cutterhead

Heat generated during EPB tunnelling. Muck temperature can be 60 + degrees C

Blockage

Blockage
Some issues with mixed faces of rock and soil

Major risk factor for large settlement and sinkholes
If we want to relate problems to geological conditions, the first thing we need to know is what the geological conditions are. This is a problem in weathered rock. Extrapolations from borehole information often inaccurate (Fletcher).
Establishing rockhead level from boreholes

Initial interpretation, slurry TBM in granitic Gneiss
Establishing rockhead level from boreholes

Initial interpretation

Re-interpretation

Actual ground conditions observed in tunnel different from re-interpretation
What we see during TBM advance
Interventions – opportunity to map the face

Limitations:
- Limited openings
- Generally spoil up to axis level
- Training of staff fit for compressed air
Pressurised TBMs

- Numerous parameters measured within the TBM during tunnelling
- Analysis of the data can be used to:
  - Aid in assessing whether the TBM is in soil, mixed ground or rock
  - The strength of the rock encountered
  - Choice of slurry, EPB or variable density TBMs
  - The effect of the various ground conditions on TBM advance rates, tool consumption
  - Suggest what improvements can be made to the TBM or tunnelling procedures to improve tunnelling performance
Method of assessment of ground conditions

- Boreholes and face logs (from interventions) give occasional fixed information
- TBM data – the only available information that is continuous
  - Express as Penetration Index (Contact Force per cutter/advance per revolution) or Specific Energy (Torque per sq.m of face/advance rate)
  - Calibrated against data from boreholes and face logs
Tunnel A

- 9.23m diameter EPB drive
- 53 No 17” discs
- 1.8m long rings
- Tuff rock and soil grades of weathered tuff
- Average CAI of rock: 3.5
- Geological section from boreholes that were mostly significantly offset

Direction of drive
Tunnel A, Penetration Index

EPB, mainly soil, max 2.74 bar

Open mode, mainly rock, <0.5 bar

EPB, mixed & soil, max 3.14 bar

Penetration Index, MN/m

Ring Number
Tunnel A, Specific Energy

EPB, mainly soil, max 2.74 bar

Open mode, mainly rock, <0.5 bar

EPB, mixed & soil, max 3.14 bar

Specific Energy (MJ/m³)

Ring Number

0 100 200 300 400 500 600
Based on known ground conditions at interventions, on line boreholes
Deviation in Penetration Index from trend

\[ y = 0.3309x + 13.004 \]
Max value 376 Mj/m³, at known rock / soil interface, but not mapped
Mixed Ground categories – Tunnel A

Use all of the data:
- Boreholes (within 3m)
- Face logs
- TBM data

To reassess geology along the drive

Categories of ground condition for Tunnel B:
- <15% rock
- All rock
- >15% but <50% rock
- >50% but <85% rock
- >85% rock
- <15% rock
Tunnel A - Average instantaneous advance rate

![Bar chart showing average instantaneous advance rate for different proportions of rock.](chart.png)

- **<15% Rock**: 26.23 mm/min
- **15% to 50%**: 15.16 mm/min
- **50% to 85%**: 9.08 mm/min
- **85% to 99.9%**: 4.60 mm/min
- **Rock**: 10.26 mm/min
Tunnel A – $m^3$ per 17” disc

Volume of ground excavated per disc cutter change, $m^3$

<table>
<thead>
<tr>
<th>Proportion of rock</th>
<th>Volume of excavation, $m^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;15% Rock</td>
<td>804</td>
</tr>
<tr>
<td>15% to 50%</td>
<td>366</td>
</tr>
<tr>
<td>50% to 85%</td>
<td>119</td>
</tr>
<tr>
<td>85% to 99.9%</td>
<td>18</td>
</tr>
<tr>
<td>100% Rock</td>
<td>131</td>
</tr>
</tbody>
</table>
Tunnel A - Length of tunnel per intervention

- <15% Rock: 74.06 m
- 15% to 50%: 30.76 m
- 50% to 85%: 11.45 m
- 85% to 99.9%: 3.20 m
- Rock: 6.35 m
Coarse particle clogging

‘Tool gap’. Typically 150mm to 200mm

Material we are trying to get to flow, when cutting rock – mostly 50mm to 75mm rock fragments. In EPB mode under high contact forces.
Components of time for TBM tunnelling

- Ground related
  - TBM advancing
  - Intervention time

- Not ground related
  - Ring build
  - Other maintenance
  - Extension of cables, pipework, rails
  - Other delays
1.65% of the tunnel drive in 85% to 99.9% rock
Required 33% of the total time for TBM advance + interventions
In mixed ground of soil and strong rock, with >50% rock:
- Very slow advance speed
- Very rapid tool wear & damage
- Very frequent interventions
- Very long interventions
- High heat, with extended flushing required to make safe for intervention

Extended flushing, long & frequent interventions increase risk of instability/sinkhole formation
Tunnel B – EPB drive in mixed ground of mainly Granodiorite rock

Compared with Tunnel A:
- Different rock
- Different contractor
- Different TBM manufacturer
- A lot more tunnelling in mixed ground, high % rock
Tunnel B – EPB drive in mixed ground of mainly Granodiorite rock

CAI av. = 3.6
256m of tunnelling
116 interventions under compressed air
513 No. 17” discs changed
9.5 months to tunnel (av. 6.2m/week)

Mostly driven in semi-EPB mode, using compressed air above axis level
Tunnel C – Slurry drive in mixed ground

- 7.46m diameter slurry TBM drive
- 44 No 19” discs
- 1.5m long rings
- Granite rock and soil grades of weathered granite. Numerous intrusive dykes of rhyolite and basalt
- Average Cherchar Abrasion Index (CAI) of rock: 4.6, quartz content 30%

Direction of drive
Tunnel C – Penetration Index

Face pressure > water pressure in all conditions
Tunnel C Fine particle clogging

- Zones of Completely Decomposed Granite were unusually sticky
- Smectites (swelling clay minerals) present
Tunnel C – Specific Energy

![Graph showing specific energy distribution across ring numbers with different rock types and zones.](image)
### Tunnel C – PI/SE

#### Diagram Description:
- **X-axis**: Ring No.
- **Y-axis**: Ratio PI/SE

- **Granite rock** (pink area)
- **Mixed** (purple area)
- **Cl cdg**

#### Data Points:
- Various data points representing different conditions and their respective ratios are plotted along the X and Y axes.
- Effectively advance force/torque
- High (>1) in intact rock – need a lot of force on the tools, compared with torque
- Moderate (0.4 to 1), could be:
  - Highly fractured rock
  - Mixed Ground
  - Clogging clayey cdg
- Low (<0.4) in Granular soil (cdg): cutting action of the scrapers is based on torque, rather than force
- Values probably depend on TBM design and operation, and need to be customised for each tunnel
Tunnel C - Average instantaneous advance rate

![Bar chart showing average advance rates for different ground classifications: cdg (27.00 mm/minute), clayey cdg (16.50 mm/minute), Mixed granite (15.80 mm/minute), Granite rock (15.35 mm/minute).]
Tunnel C – m³ per 19” disc

Graph showing the m³ of ground excavated per disc changed for different ground classifications:

- cdg: 161.5 m³
- cl cdg: 146.2 m³
- Mixed (granite): 191.7 m³
- Granite: 130.2 m³
**Tunnel C - Length of tunnel per intervention**

The diagram shows the average length of tunnel per intervention based on different ground classifications:

- **cdg**: Average length of 11.8 meters
- **cl cdg**: Average length of 8.4 meters
- **Mixed (granite)**: Average length of 7.1 meters
- **Granite**: Average length of 7.7 meters

This data is presented to illustrate the impact of ground conditions on tunnel construction lengths.
Tunnel C - Time per m of tunnel for advance, interventions
Tunnel C

- Graphs part of assessment of first tunnel drive
- Assessment used to justify:
  - Reduced rotation speed in clayey cdg
  - TBM for second, parallel drive altered, in particular to incorporate flushing at cutterhead
  - Slurry treatment plant upgraded to better deal with increased fines
    - Second drive had improved performance, compared with first, in clayey cdg
    - Comparison with Tunnels A and B shows how slurry shield operated in mixed ground with high % of strong rock without the problems experienced with the EPB TBMs at Tunnels A and B
    - Time for interventions is a major factor in TBM tunnelling in weathered rock
<table>
<thead>
<tr>
<th>Major Projects</th>
<th>Tunnelling complete</th>
<th>TBMs: Numbers used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td></td>
<td><strong>EPB</strong></td>
</tr>
<tr>
<td>East-West Line</td>
<td>1987</td>
<td>2</td>
</tr>
<tr>
<td>North East Line (NEL)</td>
<td>2001</td>
<td>14</td>
</tr>
<tr>
<td>Deep Sewer Tunnels (1)</td>
<td>2005</td>
<td>8</td>
</tr>
<tr>
<td>Circle line (CCL)</td>
<td>2009</td>
<td>19</td>
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<tr>
<td>Downtown Line (DTL)</td>
<td>2014</td>
<td>42</td>
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<tr>
<td>Deep Cable Tunnels</td>
<td>In progress</td>
<td>3</td>
</tr>
<tr>
<td>Thomson – East Coast</td>
<td>In progress</td>
<td>28</td>
</tr>
<tr>
<td>Cross-Island Line</td>
<td>Planning</td>
<td>?</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>116+</strong></td>
<td><strong>51+</strong></td>
</tr>
</tbody>
</table>

30 years of PTBM in Singapore (>5m diameter)
Singapore – current practice

Granite and Norite. Mostly slurry

Old Alluvium. All EPB

Jurong. Sedimentary and metamorphic rock. Some EPB, Some slurry

Kallang. Recent soils, soft, marine clay. All EPB
Mixed face tunnelling

- In Singapore and Hong Kong owners now commonly specify use of slurry TBMs in the most adverse mixed ground conditions. If owners don’t specify, they will almost always get, in a competitive tender, an EPB, and, in adverse mixed ground conditions, the potential of long delays and large claims.
Compressed air interventions – weathered rock

- Spending as long or longer on interventions as advancing the TBM

French tables (oxygen decompression)

German tables (oxygen decompression)

Small reduction in pressure can significantly increase working time per shift for interventions, if safe to do so.
Deriving strength of rock from TBM parameters

Equations developed by Colorado School of Mines
For massive or widely jointed rock
Cubic relationship between UCS and advance speed, for given force on cutter
For typical mixed ground machines, only applicable to strong or stronger rock – below a UCS of 100MPa other factors control

For Strong or stronger rock, increase in UCS of 20% results in:
- 42% reduction in penetration/revolution
- 73% increase in disc consumption per m$^3$ excavated
Penetration of 17” disc
Derived strength of granitic Gneiss, Tunnel D
Questions