TBM "Boreability" in Hard Rock

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Outline

- Introduction
- What is rock boreability?
- Drillability
- Rock mass assessments
- Conclusive remarks
Tunnel Boring Machine (TBM)
TBMs in faulted rock

Rostami (2016)
Open TBM for hard rock

www.herrenknecht.com
Cutterhead and cutter discs
Hard rock tunnel boring

- Intact rock
  - Strength
  - Brittleness
  - Porosity
  - Surface hardness
  - Abrasivity
  - …

- Rock mass
  - Plane of weakness
  - Orientation
  - Weakness zones
  - Groundwater
  - In-situ stress
  - …

- Cutter discs:
  - Diameter
  - Number
  - Spacing
  - Others

- TBM diameter
- Cutterhead rpm
- Thrust

Modified from Robbins
Hard rock tunnel boring
Rock boreability

• TBM boreability can be defined as:

The resistance (in terms of ease or difficulty) encountered by a TBM as it penetrates a rock mass (intact rock containing planes of weakness)

• Intact rock – Drillability

• Rock mass
Rock boreability

\[ i_0 = \left( \frac{M_t}{M_1} \right)^b \] (mm/rev)

- \( i_0 \) = basic penetration rate
- \( M_t \) = gross cutter thrust
- \( M_1 \) = critical cutter thrust
- \( b \) = penetration coefficient

Modified from Bruland (2000)
Rock drillability

"Ability of the intact rock to be drilled or bored"

"Influence that intact rock properties on performance prediction and cost evaluations"

Breakability

Abrasivity
Rock drillability

Main intact rock properties
- Strength
- Brittleness
- Surface hardness
- Wear capacity
Rock drillability

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Main intact rock properties

- Strength
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Laboratory test methods: "Breakability"
Laboratory test methods: "Breakability"
Laboratory test methods: "Abrasivity"
Rock abrasivity testing

Cerchar abrasivity test

LCPC test

Abrasion Value cutter Steel (AVS) test
Drillability assessments for hard rock

- Uniaxial Compressive Strength (UCS)
- Rock Toughness
- Drilling Rate Index (DRI)
- Cutter Life Index (CLI)
- Cerchar (CAI)
Laboratory test methods: "Breakability"
Drillability assessments for hard rock

- Drilling Rate Index (DRI)
- Cutter Life Index (CLI)
Drillability assessments for hard rock
Drillability assessments for hard rock

- Drilling Rate Index (DRI)
- Cutter Life Index (CLI)
Laboratory test methods “cutter wear”
Rock Mass Assessments

- There is no single parameter that can fully represent the properties of jointed rock masses

<table>
<thead>
<tr>
<th>Rock mass classification</th>
<th>Author</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock Quality Designation (RQD)</td>
<td>D.U. Deere</td>
<td>1964</td>
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<tr>
<td>Rock Mass Rating (RMR)</td>
<td>Z.T. Bieniawki</td>
<td>1973</td>
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<tr>
<td>Rock Tunnelling Quality Index (Q)</td>
<td>N. Barton, R. Lien and J. Lunde</td>
<td>1974</td>
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<tr>
<td>Degree of fracturing (k_s factor)</td>
<td>NTNU (NTH)</td>
<td>1981</td>
</tr>
<tr>
<td>Rock Mass Index (RMi)</td>
<td>A. Palmström</td>
<td>1995</td>
</tr>
<tr>
<td>Geological Strength Index (GSI)</td>
<td>E. Hoek and E.T. Brown</td>
<td>1997</td>
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</tbody>
</table>
Rock Mass Assessments

• In hard rock tunnel boring:
  – Discontinuities or planes of weakness in a rock mass contribute considerably to net penetration rate and cutter wear
  – Degree of fracturing
  – Orientation regarding to the tunnel alignment
  – Joint characteristics (filling, persistence…)
  – In/situ stress
  – …
## Rock Mass Assessments

<table>
<thead>
<tr>
<th>Fracture Class (Sf)</th>
<th>Average spacing between fractures (a_r) (cm)</th>
<th>Range class (cm)</th>
<th>Degree of fracturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(\infty)</td>
<td>480 – (\infty)</td>
<td>Non-fractured</td>
</tr>
<tr>
<td>1</td>
<td>320</td>
<td>240 – 480</td>
<td>Extremely low</td>
</tr>
<tr>
<td>2</td>
<td>160</td>
<td>120 – 240</td>
<td>Very low</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>60 – 120</td>
<td>Low</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>30 – 60</td>
<td>Medium</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>15 – 30</td>
<td>High</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>7.5 – 15</td>
<td>Very high</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>4 – 7.5</td>
<td>Extremely high</td>
</tr>
</tbody>
</table>
Rock Mass Assessments

![Diagram showing tunnel axis and rock mass orientations at 0°, 60°, and 90° angles.]

- Tunnel axis
- Orientations: 0°, 60°, 90°
Rock Mass Assessments
Rock Mass Assessments

Tunnel axis: 160°

Approx. 1 m
Rock Mass Assessments
Rock Mass Assessments

![Rock Mass Diagram]

- **Intact rock**
- **Rock mass**
  - MSJ
  - Fractures
  - Schistosity
  - Microcracks

Length (m): 0.001 to 100
Rock Mass Assessments
Rock Mass Assessments

- Geological back-mapping & core-logging
- Understanding rock mass boreability for hard rock TBM
- Chip analysis
- Tunnel face inspection
Rock Mass Assessments

- Existing fracture?
- Cutter edge indentations
- Radial crack
Conclusive remarks

• ‘Rock mass boreability’ is a comprehensive parameter:
  – Intact rock properties
  – Rock mass parameters

• Rock mass fracturing is found to be the geological factor that exerts the greatest influence on net penetration rate

• More effort should be emphasized on understanding the rock breaking process and tool wear tribological system
Takk!

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Rock mass influence

**Low boreability**

$k_{ekv} = 0.3$

Spacing: 300 cm

$\alpha = 20$

$k_s = 0.4$

DRI=35

**High boreability**

$k_{ekv} = 1.7$

Spacing: 10 cm

$\alpha = 20$

$k_s = 1.55$

DRI=65