TBM PERFORMANCE OVERVIEW, AND WHY THE QTBM PROGNOSIS MODEL

Nick Barton, NB&A, Oslo (Høvik)

www.nickbarton.com
CONTENT of LECTURE

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3. CASE-RECORD SURVEY for OPEN-GRIPPER and DOUBLE-SHIELD TBM
4. WORLD-RECORD TBM PERFORMANCE
5. TBM DELAYS IN FAULT ZONES – SEVERAL EXAMPLES
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8. IS IT CORRECT TO USE TBM ‘BECAUSE ROCK CONDITIONS WILL BE SO BAD’?
9. QTBM PROGNOSIS DEVELOPMENT: Q WITH MACHINE-ROCK INTERACTION
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1. SOME FUNDAMENTALS: *PR* and *AR*
**PENETRATION RATE (PR)** IS FOR CONTINUOUS (SHORT-TERM) BORING.

**ADVANCE RATE (AR)** IS ACTUAL RATE OF TUNNEL ADVANCE: INCLUDE STOPS.

Shale, tillite, sandstone $\sigma_c = 50, 125, 250$ MPa. (Fawcett, 1993 data, plotted in Barton 2000).

$AR = PR \times U$ (?)
EVIDENCE LINKING Q-VALUES WITH PR:
2.85 km in granites, Malaysia.

Q-values with all joints included (not just least favourable Jr/Ja)
(Sundaram and Rafek, 1998)
LOGICAL TRENDS: high $Q$, high $\sigma_c$, lower PR

(After Innaurato et al. 1991)
2. CUTTER FORCE VERSUS ROCK MASS STRENGTH
CUTTER THRUST COMPARED TO ROCK MASS STRENGTH
(Figures from Grandori et al. 1995)

LEFT: WHAT TO EXPECT IF ENOUGH POWER FOR HIGH THRUST

BELOW: IF ROCK IS TOO HARD

FOR REALISTIC TBM PROGNOSIS MUST COMPARE CUTTER THRUST (F) WITH ROCK MASS STRENGTH
UNDER-POWERED TBM FROM 1980’s.

REDUCED PR DESPITE INCREASED THRUST/CUTTER.

% HARD LIMESTONE SHOWN. (NELSON ET AL. 1983).

(40 MPa / 130 MPa)
TBM PROGNOSIS FAILS TO PREDICT REDUCED PROGRESS WITH INCREASED CUTTER THRUST. TBM UNDER-POWERED IN RELATION TO VERY HARD META-SANDSTONES. JOINTING / ROCK STRENGTH (?) INCORRECTLY MODELLED. (McKelvey, Blindheim et al. 1996)
CUTTER LIFE INDEX (CLI).............NTH/NTNU
1994.....used in two places in Qtbm
3. CASE-RECORD SURVEY for OPEN-GRIPPER and DOUBLE-SHIELD TBM

4. WORLD-RECORD TBM PERFORMANCES ALSO SHOW DECELERATION WITH TIME
CASE RECORD EVIDENCE OF DECELERATION from 145 cases representing 1000 km of TBM

(Mostly open-gripper cases)

Conventional equation:

\[ AR = PR \times U \]

but reality is:

\[ AR = PR \cdot T^m \]
BEST

MEAN

WORST

Note: no horizontal lines.

(U cannot be constant WITH TIME/LENGTH)
## ROBBINS WEB SITE.

### TBM RECORDS

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Best Day</th>
<th>Best Week</th>
<th>Best Month</th>
<th>Monthly Average for Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 - 4 m</td>
<td>172 m Robbins Katoomba Australia</td>
<td>703 m Robbins Katoomba Australia</td>
<td>2163 m Robbins Oso USA</td>
<td>1189 m Robbins Katoomba Australia</td>
</tr>
<tr>
<td>4 - 5 m</td>
<td>128 m Robbins SSC No. 4 USA</td>
<td>477 m Robbins SSC No. 4 USA</td>
<td>1822 m Robbins Yellow River China</td>
<td>1352 m Robbins Yellow River China</td>
</tr>
<tr>
<td>5 - 6 m</td>
<td>99 m Robbins Little Calumet USA</td>
<td>562 m Robbins Little Calumet USA</td>
<td>2163 m Robbins Little Calumet USA</td>
<td>1095 m Robbins Yindarugan China</td>
</tr>
<tr>
<td>6 - 7 m</td>
<td>114 m Robbins Dallas Metro USA</td>
<td>500 m Robbins Dallas Metro USA</td>
<td>1690 m Robbins Dallas Metro USA</td>
<td>1187 m Robbins Dallas Metro USA</td>
</tr>
</tbody>
</table>

### Best Day
- 172 m one day!
- 703 m one week!
- 2163 m one month!
- (16 km one year!)

### Best Monthly Average
- ‘ONLY’ 1352 m.

### UK Chalk Marl: UCS 5-9 MPa
WORLD RECORDS BY TBM – ASSEMBLED BY ROBBINS: GET FOLLOWING RESULTS WHEN SIZES COMBINED TO REDUCE SCATTER.

Assume 24 hrs/day, 168 hrs/week, 720 hrs/month. (Barton, 2013).

World record drill-and-blast
SVEA TUNNEL
5.8 km 54 weeks
EXAMPLES OF DOUBLE-SHIELD

1. GOOD RESULT BUT TOUGH (mean PR 2 m/hr)
2. TOUGH all the way (TOO HIGH RMR/Q)
GUADARRAMA 4 x DOUBLE-SHIELD TBM, 14 km EACH, 30-33 MONTHS.
GUADARRAMA TUNNELS SPAIN

CUTTERS MAY WEAR OUT ‘TOO FAST’ IN HARD ABRASIVE (LOW CLI) ROCKS.

THIS IS ONE OF THE REASONS FOR AR < PR.
‘Learning curve’ for double-shield TBM, struggling with very high RMR, very high Q.

(Compare with Guadarrama: blue circles = best day, week, month)
5. TBM DELAYS IN FAULT ZONES:
FAULT ZONES ARE UNIQUE CHALLENGES FOR TUNNELLERS IN GENERAL *(and for TBM in particular)* BECAUSE.......

RQD, Jn, Jr, Ja, Jw, SRF........

all the Q-parameters *(and everybody else’s parameters!)* may be adverse, also TIME + COST
FAULT ZONES (WITH LOW Q-VALUES) ARE NOT SUPPOSED TO BE ‘UNEXPECTED EVENTS’

BUT OFTEN ARE BECAUSE NO PROBE DRILLING, DUE TO THE ‘TEMPTATION’ OF HIGH-SPEED TBM TUNNELLING
EVINOS-MORNOS WATER TUNNEL, GREECE

Fault zones also create problems for double-shield TBM – if zone is not pre-treated (following probe-drilling discovery) (Grandori et al., 1995).

Lessen: Avoid TBM withdrawal.
DISTINCT ELEMENT UDEC MODELS SUGGEST POTENTIAL ‘TRAUMA’ IN (heavily fractured) FAULT ZONES

i.e. DEEP EDZ.

(Shen and Barton, 1997)
LOW ROCK QUALITY IS ASSOCIATED WITH LOW P-WAVE VELOCITY.

WHEN STRESS IS LOWERED BY WITHDRAWING A TBM IN A FAULT ZONE

VELOCITY (AND EFFECTIVE QUALITY) MAY BE REDUCED.
BECAUSE VELOCITY $V_p$ IS STRESS-DEPENDENT, STRESS RELEASE (BY WITHDRAWING A TBM) HAS AN ADVERSE EFFECT ON PROPERTIES AND STAND-UP TIME (Barton, 2006)
CHILE MINE TUNNEL
DOUBLE-SHIELD MACHINE
‘OVER-EXCAVATED’ IN
THIS FAULTED ZONE.

WHEN $\text{Jn/Jr} \geq 6$, OVER-
BREAK OR OVER-BORING
IS LIKELY

$Q \approx \frac{40}{15} \times \frac{1.5}{4} \times \frac{1.0}{2.5} = 0.4$ ‘very poor’

...............(i.e. $\text{Jn/Jr} \geq 6$)
OVERBREAK WITH \( \frac{J_n}{J_r} \geq 6 \)

\[ J_n = \text{number of sets} \]
\[ J_r = \text{roughness} \]

\[
\begin{array}{ll}
6/1.0 & 9/1.5 \\
12/2 & 15/3 \\
\end{array}
\]

(DESPITE FOUR JOINT SETS, TOO MUCH ROUGHNESS AND DILATION)

In photos:
\[ \frac{J_n}{J_r} = 9/(1-1.5) \]
IF FAULTED ROCK NOT ANTICIPATED, NOT PROBE-DRILLED, NOR PRE-TREATED, MAY CAUSE ‘OVER-EXCAVATION’
= VOID FORMATION

(e.g. 15-25 m/day reduction to 2.5-5 m/day, FOR ≈ 1 MONTH in Chile)
'WAITING FOR THE TRAIN' is a known expression on 'PIE DIAGRAMS'.
'WAITING FOR THE SMOKE' (to clear) IS FORTUNATELY LESS COMMON.
(CAUSED BY BIG VOLUME OF CHEMICAL GROUT CATCHING FIRE)
THIS SUB-PARALLEL FAULT DELAYED THE PROJECT 30m/5 months. SHAFT ERODED BY WATER AND FALLING BLOCKS. FINALLY D+B TO COMPLETE. 
(Figures, photos, Karl G.Holter, NB) ........EXTREME –m VALUE
WET TBM TUNNEL IN FAULTED LIMESTONES (both ‘ends’ – two TBM delayed). Equivalent Q-values very low due to extremely low Jw-factor.
(Initially 1 and 4 m3/sec inrushes at each ‘end’: the biggest with fault debris).

DECELERATION (-m GRADIENT) IS VERY LARGE, time T > 10,000 hours delay).
6. DECELERATION (-m) ACCENTUATED IN FAULT ZONES – ONE EQUATION NEEDED
DECELERATION GRADIENTS (-m) ARE Q-VALUE RELATED: WHEN Q < 1. BUT Q CAN BE IMPROVED BY PRE-GROUTING!

*improves many Q-parameters, reduces negative –m*)

Rock mass quality  \( Q = \left( \frac{RQD}{J_n} \right) \times \left( \frac{J_r}{J_a} \right) \times \left( \frac{J_w}{SRF} \right) \)
‘THEO – EMPIRICAL’ REASONS WHY FAULT ZONES ARE SO DIFFICULT FOR TBM.

We need three basic equations:

1. \( AR = PR \times U \) (all TBM must follow this)

2. \( U = T^m \) (decelerating advance rate means time-dependent \( U \))

3. \( T = \frac{L}{AR} \) (time for length \( L \) depends on \( AR \)......as when walking)

Therefore we have the following:

4. \( T = \frac{L}{(PR \times T^m)} \) (from #1, #2 and #3)

5. \( T = \left( \frac{L}{PR} \right)^{\frac{1}{1+m}} \)

VERY important for TBM......because very negative (-)m values make the \( \frac{1}{1+m} \) component TOO LARGE......time \( T \) gets too long (months or years)!
7. IS IT CORRECT TO USE TBM: ‘BECAUSE THE TUNNEL IS SO LONG’?

8. IS IT CORRECT TO USE TBM: ‘BECAUSE ROCK CONDITIONS WILL BE SO BAD’?
$T_1 = 5 \text{ km}$

5 km, better investigated, fewer ‘extremes’, lower cover – probably.

$T_2 = 25 \text{ km}$

25 km, much less investigated, maybe many ‘extremes’
CENTRAL Q-VALUES AND $Q_{TBM}$ VALUES BEST FOR TBM. TAIL-DISTRIBUTIONS (of Q) ARE ‘faster’ WITH D+B!

Record for drill-and-blast:

150m/BEST week (SVEA)

Whole project 104 m/week average, 5.8 km

Achilles Heel for TBM? Unless pre-injected.

Too frequent cutter change.
9. QTBm PROGNOSIS DEVELOPMENT: QU WITH MACHINE-ROCK INTERACTION
DEVELOPMENT of $Q_{TBM}$ (extra parameters appended to Q). Analysis of case records TOOK SIX MONTHS, WHILE WRITING THIS BOOK AND THE FIRST ARTICLE, both in 1999.
THE $Q_{TBM}$ MODEL FOR TBM PROGNOSIS

involves $Q$, and machine/rock interaction ‘normalizations’

$$Q_{TBM} = \frac{RQD_o}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \times \frac{SIGMA}{(F^{10}/20^9)} \times \frac{20}{CLI} \times \frac{q}{20} \times \frac{\sigma_\theta}{5}$$

$$SIGMA \approx 5 \gamma Q_c^{1/3}$$

$$PR \approx 5 Q_{TBM}^{-1/5}$$
THE Q_{TBM} EQUATION WAS DEVELOPED BY TRIAL AND ERROR.

MOST ADDITIONS TO Q-PARAMETERS ARE ‘NORMALIZED BY CENTRAL VALUES’
THE THREE Q\textsubscript{TBM} SCREENS
\textit{(DETAILS SHOWN LATER)}
DEVELOPED FROM NB EQUATIONS
BY Ricardo Abrahão, RAGeociencias
Example of single-shield (◻) and double-shield (★) (F = 28 or 26 tnf).
(Note: untreated major fault (LOWEST LINE) stops TBM ‘for ever’.... in simulation)
The All Conditions Tunneler (ACT) TBM developed by Robbins utilizes a retractable telescopic shield to allow ground treatment in front of or close to the face while providing the protection of a shield body.

Robbins ALL CONDITIONS TUNNELLER (ACT) LOOKS VERY PROMISING for PRE-TREATING FAULT ZONES (Willis, 2012)
12. $Q_{TBM}$ PROGNOSIS FOR HARD-JOINTED-ROCK AND FAULTS: EXAMPLE
A ‘HARD-ROCK-WITH-FAULTS’ PROGNOSIS FOR TBM TUNNELS NEAR OSLO.

2 X 9.6 km + 2 X 7.9 km

(when analysis done)
Northern tunnel(s) of 2 x 9.6 km pass near here, on east side of Oslo Fjord
SUMMARY OF Q-VALUES FOR 330 ROCK CUTTINGS (nine-per-box) FOR BOTH TUNNELS

NOTE: CUTTINGS (EXPOSURES) GIVE ROCK MASS Q-CLASSES 1 TO 5

WEAKNESS ZONES / FAULTS GIVE Q-CLASSES 6 TO 8 (LOW VP, LOW Q IN CORE-LOGGING)
SUMMARY OF Q-VALUE STATISTICS (classes 1 to 5) FOR SOUTHERN TUNNELS.

(Fault zones treated separately, using core-logging and seismic refraction)
EXAMPLE OF CLASS 1 ROCK MASS:

MAY GIVE SLOW PR WITH TBM (BUT PERFECT FOR DRILL-AND-BLAST)
**ADDING THE OBSERVATIONS:** example of frequency of RQD, Jn and Jr Tunnel South.

### Table: Rock Quality Designation (RQD)

<table>
<thead>
<tr>
<th>Location</th>
<th>TUNNEL SOUTH</th>
<th>Depth / chainage: ROCK EXPOSURES LOGGED</th>
<th>Date: 30.08.09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numbers for domains, core boxes, tunnel lengths</td>
<td>JBV ÅSLAND - LANGHUS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q (typical range)</td>
<td>0.1 - 100</td>
<td>Q (mean)</td>
<td>11.1</td>
</tr>
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<td>(4 - 15) x (1 - 5) x (0.5 - 1.0)</td>
<td>(98/4) x (1.3) x (0.75 - 1.0)</td>
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### Table: Joint Number (Jn)

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### Table: Joint Roughness (Jr)

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INPUT-DATA SCREEN FOR ASSUMED CLASS 1 ROCK MASS.

MANY ADVERSE CHARACTERISTICS FOR TBM: hard rock, too few joints, LOW PR).
NORTH TUNNELS

Comparing open-gripper TBM (top) and double-shield TBM (bottom).

(37.9 months or optimistic (1/2 x –m) 17.5 months, both without weakness zones).
ACCUMULATED TIME FOR NINE SIMULATED WEAKNESS ZONES = 2.9 MONTHS.

NOTE USE OF $V_p$
(For shallow parts of tunnel, can use refraction seismic)
CONCLUSIONS

1. Whether single-shield or double-shield, must probe-drill and high-pressure (5 to 10 MPa) pre-inject major fault zones, to improve rock mass quality and to displace water ($J_w$). If too much silt and clay, need jet grouting.

2. Pre-injection helps to improve most of the six Q-parameters, so (-m) less negative. This means fewer long delays for the TBM, despite the time needed for the pre-injections.

3. Do not ‘automatically’ choose TBM for long tunnels. A ‘hybrid’ solution might have advantages. Drill-and-blast the deeper and less investigated sections, if intermediate access is possible. Help maintain the good reputation of TBM!

4. Descriptions of the rock mass are limited to each maintenance shift in double-shield with PC-elements. So double-shield case records are often unreliable in relation to rock mass descriptions.