TBM PERFORMANCE PREDICTION BACKGROUND AND STATE-OF-THE-ART

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OUTLINE
- Introduction
- Definitions
- Performance prediction for soft ground machines
- Performance prediction for hard rock TBM
  - Empirical Models
  - Force Equilibrium Model
- Estimating machine utilization
  - Existing Models
  - Simulation
- Implications in difficult ground
- Conclusions
"THANK YOU FOR SENDING ME A COPY OF YOUR BOOK; I'LL WASTE NO TIME READING IT."

Moses Hadas

INTRODUCTION

- Performance Prediction is a Key to:
  - Production or Advance Rate Estimates
  - Project Schedule and Cost
  - Feasibility Analysis
  - Machine Selection
- Predictor Models:
  - Empirical (based on the field data)
  - Theoretical (based on the cutting forces)
- Universal VS Site specific models
- Output:
  - Rate of Advance
  - Cutter life and cost estimate
DEFINITIONS

- **Penetration**: The amount of penetration per revolution of the head (mm/rev or in/rev)
- **ROP**: Rate of penetration is the speed of cutterhead penetrating the face or rate of face advance while excavating (m/hr or ft/hr). Also referred to as Instantaneous Penetration Rate
- **RPM**: Cutterhead Rotational Speed revolution per minute
- **Head Speed**: The speed of head moving across the face or into the face. It is a multiplication of penetration and RPM (m/hr or ft/hr).
- **IPR**: Instantaneous Production Rate also referred to as Instantaneous Cutting Rate (ICR) is the rate of production while cutting (yd³/hr or m³/hr)
- **Utilization**: Portion of time when machine is actually cutting (%)
- **AR**: Advance rate, rate of advance of the face per day/shift (m/day, ft/day)
DEFINITIONS

- ROP = Penetration . RPM
- Utilization = \( \frac{\text{Excavation Time}}{\text{Total Time}} \)
- AR = ROP . Utilization
- IPR = ROP . Face Area

DEFINITIONS

- Advance Cycle (Excavation or Boring Cycle): a full cycle includes the excavation and ground support installation to the point where the next cycle can start.
- Single Shield: Linear \( \rightarrow \) Excavation + Ground Support Installation
  
  ![Excavation Support installation diagram]

- Double Shield TBMs
  Parallel \( \rightarrow \) The larger of Excavation or Ground Support
  
  ![Excavation Ground Support diagram]

- Open TBM \( \rightarrow \) Mine + regrip
DEFINITIONS

- Total Time = Advance Cycles + Down Times
- Working in Linear or Parallel fashion. Meaning performing parallel tasks (i.e. cutter change while performing maintenance or ground support . . .)
- Machine Availability (Typically >80%) = \[
\frac{\text{Total time} - \text{Machine maintenance/repair time}}{\text{Total Time}}\]

SHIFT TIME BREAKTIME - TBMS

<table>
<thead>
<tr>
<th>BORING</th>
<th>EQUIPMENT DOWNTIMES</th>
<th>NON-EQUIPMENT DELAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time spent excavating material at the face</td>
<td>Cutter changes Stroke / restroke unscheduled maintenance (unexpected breakage) scheduled maintenance</td>
<td>System delays Suveying delays Water inflow delays Grout curtain delays Back-up mucking system delays Utilities delays (extending cables, etc.) Temporary support delays Labor delays Lunches, shift changes, etc.</td>
</tr>
</tbody>
</table>
DEFINITIONS

- Levels of Accuracy of Performance predictions
  - Rough Estimates, Based on general machine and rock characteristics, (i.e. Specific Energy Method)
  - Workable Estimates: Based on specific machine and rock characteristics, using machine specs., rock strength measurements etc.
  - Accurate Estimates: Based on full scale cutting tests, using actual cutters in blocks of rock under close field conditions and same cutting geometry

PARAMETERS INFLUENCING MACHINE PERFORMANCE

- Rock Physical Properties
- Rock Mass Properties
- Cutter Type and Geometry
- Cutterhead Design
- Machine Specifications
- Back up System
- Site Planning/Management
TYPICAL APPROACH TO APPLICATION OF MECHANICAL EXCAVATION SYSTEMS

- Geology & Rock/Coal Strength
- Purpose and Application
- Cutting Tool Selection
- Cutting Geometry (Spacing)
- Machine Thrust Torque, and Power Requirements
- Back Up System Ground Support, Transportation, etc.
- Production and Cost Estimates
- Cutting Head Profile Design and Lacing
- Bit Allocation and Head Balancing (Minimized Variation/Vibration)

COMMONLY USED ROCK PHYSICAL PROPERTY TESTS

- Uniaxial Compressive Strength (UCS)
- Brazilian (Indirect) Tensile Strength (BTS)
- Punch Penetration Test
- Thin Section Petrographic Analysis
- Cerchar Abrasivity Index (CAI)
- Triaxial Strength
- Acoustic Velocities
- Boreability Index properties
  - DRI, CLI, BWI
  - Total Hardness $H_T$
CHIPPING MECHANISM IN MASSIVE ROCKS

ROCK CHIPPING MECHANISM IN FOLIATED ROCK

(Project Report I-94, Hard Rock Tunnel Boring, University of Trondheim)
CHIPPING MECHANISM PARALLEL TO BEDDING

TUNNELING PERPENDICULAR TO BEDDING, SIDE VIEW
TUNNELING PERPENDICULAR TO BEDDING, TUNNELING FACE

CHIPPING MECHANISM PERPENDICULAR TO BEDDING
LINEAR CUTTING TESTS

ROCK MASS PROPERTIES

- Number of Joint Sets
  - JS, Joint frequency, RQD
- Type of Joints
- Spacing Between the Joints
- Orientation of the Joints
JOINT EFFECTS

![Graph showing joint effects](Project Report I-94, Hard Rock Tunnel Boring, University of Trondheim)

MACHINE PARAMETERS

- Used/Existing Machine
  - Cutter Type
  - Layout, Spacing and Allocation
  - Machine Specifications
    - Thrust
    - Torque
    - Power
- New Machine
GENERIC METHOD, SPECIFIC ENERGY METHOD

For all types of machines

SPECIFIC ENERGY METHOD

\[ IPR = \frac{HP \cdot \eta}{SE} \]

IPR = Production Rate (ton/hr)
HP = Machine Power (hp)
\( \eta \) = Mechanical Efficiency (%)
SE = Specific Energy (hp-hr/ton)

\[ ROP = \frac{IPR}{A} \]

A = Face Area (m²)
**TBM PERFORMANCE PREDICTION**

- Volume Based
- Fixed Rates (ROP 30-100 mm/min for 10-3 m Dia) to maintain the balance between the material excavated and machine penetration.
- Advance rate limited by support installation
  
  **Advance Cycle =**
  
  Time for excavation + Time for segment installation
  
  (adding pipe in pipe jacking)
- Typical strokes of 1-1.5 m (length of segments) in 20-30 minutes, another 20 min for segment installation or roughly 1 m/hr and 10-20 m/day

**PERFORMANCE PREDICTION OF SHIELDS AND MICROTUNNELING (SOFT GROUND) MACHINES**
EXAMPLE OF SOFT GROUND MACHINES

- 20 ft (6 m) diameter EPB,
- Rate of penetration 2.5 in/min (63 mm/min)
- \( \Rightarrow \) ROP = 150 in/min = 12.5 ft/hr
- Utilization of 20% and 3 shift, 24 hr work days
- \( \Rightarrow \) Daily advance rate = \(0.2 \times 24 \times 12.5 = 60 \) ft/day
- 5 ft rings = 12 rings /day
- Excavation cycle = \( \frac{5}{12.5} = 0.4 \) hr = 24 minutes
- Lining = segmental lining, 5 + 1, erected every 20 minutes
- \( \Rightarrow \) Advance cycle = 24 + 20 = 44 minutes

PERFORMANCE PREDICTION OF ROCK TBMS

- **Empirical Method**
  - Based on the TBM field data,
  - Includes field performance and rock mass parameters
  - Examples: NTNU or Norwegian Model, Tarkoy Model, Nelson FPI Model,
  - **others . . .**

- **Semi-Theoretical or Force Equilibrium Method**
  - Based on rock cutting forces
  - Very robust and can include cutterhead design and machine specifications,
  - Used by major machine manufacturers,
  - Examples: Rostami or CSM Model, Sato, Sanyo, Ozdemir, Wijk, Others . . .
EMPIRICAL MODELS

**Advantages**
- Proven based on observed field performance of the TBMs in the field
- Accounts for TBM as the whole system,
- Many of field adjustments (i.e. average cutter conditions) are implied.
- Ability to account for rock joints and rock mass properties

**Disadvantages**
- Lower accuracy when used in cases when input parameters are beyond what was in the original field performance database
- Unable to account for variations in cutter and cutterhead geometry, i.e. cutter tip width, diameter, spacing, gage arrangement
- Extremely sensitive to rock joint properties

THEORETICAL MODELS

**Advantages**
- Flexible with cutter geometry and machine specifications
- Can be used in trade off between thrust and torque and optimization
- Can be used for cutterhead design and improvements
- Can explain the actual working condition of the discs and related forces

**Disadvantages**
- Unable to easily account for rock mass parameters
- Lack of accounting for joints
- Can be off by a good margin in jointed rock
- Inability to account for required field adjustments
"He uses statistics as a drunken man uses lamp-posts...for support rather than illumination."

- Andrew Lang (1844-1912)

**INTERESTING QUOTE**

**TBM PERFORMANCE PREDICTION**

- Accuracy of models could be compromised because Machines operated under their capacity
  - Due to misreading of operational parameters
  - Higher stresses on the machine when operated at full capacity → higher maintenance, lower utilization
  - Steering/Turns
  - Lack of experience of the contractor/operator
- Machines often operated at 70-80% of their capacity
- We often try to guess what the operator is going to do
TBM PERFORMANCE PREDICTION

- TBM ROP can be estimated with reasonable degree of accuracy with current models.
- The accuracy of the models are somewhat limited by the accuracy of the input parameters.
  - Mainly the variability of the ground relative to index parameters used in the models to calculated ROP.
  - Accuracy of models suffer when machines are used in rocks with joints, especially where the jointing tends to change in frequency and orientation, blocky grounds, shear zones, and mixed face conditions.
- Further research is to account for the impact of joints on machine performance.

Norwegian Model,

Input:
- Rock mass characteristics, (joint sets, orientation, spacing)
- Specially measured indices (DRI, CLI, SJ, Abrasivity)
- Disc and machine’s general spec.s

Output:
- Basic penetration,
- Advance Rate
TBM PERFORMANCE PREDICTION

- Nelson’s Model,

Input:
- Total Hardness
- Thrust per cutter

Output:
- Basic penetration,
- Advance Rate

TYPICAL TOTAL HARDNESS OF SELECTED ROCKS

(P.J. Tarkoy 1986)
FIELD PENETRATION INDEX (FPI)

\[ FPI = \frac{F_p (kN)}{\text{Penetration (mm/rev)}} \]

kN/mm/rev

Prediction,
HT
FPI
Cutter Load
Penetration
ROP = \rho \cdot RPM

Nelson et. al., 1989

UPDATED FPI MODEL BY HASSANPOUR (2009)
EXAMPLE

- Limestone with Total Hardness of 80
- Field Penet. Index (FPI) of 115 (kips/in)
- Using 25 ton capacity cutters = 50,000 lbs or 50 Kips
- Penetration = 50/115 = 0.43 inches/rev
- For a 20 ft diameter TBM, using cutter velocity limit of 550 ft/min, RPM = 550/(20.π) = 8.75
- Rate of Penetration = p.RPM = 0.43*8.75*60/12 = 19 ft/hr (60 min/hr, 12 inch/ft)
- Utilization of 30% for a 24 hour shift
- Daily advance = 30%*24*19 = 137 ft/day
TBM PERFORMANCE PREDICTION

Rostami or CSM Model

Input:
- Rock UCS, BTS
- Disc Geometry (Dia, Tip width), and Cutting geometry (Spacing, Penetration)
- Cutterhead and Machine Specs (can be calculated by the model)

Output:
- Cutting forces (Normal and Rolling)
- Machine thrust, torque, RPM, Power
- ROP,
- Cutterhead design & Machine optimization

CSM CUTTING FORCE EQUATIONS

Normal Force:

\[ F_N = T \cdot R \cdot \Phi \cdot P_r \]

Nominal Crushed Zone Pressure:

\[ P_r = C \cdot \frac{S \cdot \sigma_c^2 \cdot \sigma_t}{\Phi \cdot \sqrt{R \cdot T}} \]

Where:
- \( F_N \) = Normal Force (lbs, kN)
- \( S \) = Spacing (in, mm)
- \( P \) = Penetration (in, mm)
- \( \sigma_t \) = Tensile Strength (Psi, MPa)
- \( \sigma_c \) = Uniaxial Compressive Strength (Psi, MPa)
- \( T \) = Tip Width (in, mm)
- \( R \) = Cutter Radius (in, mm)
- \( C \) = Constant (2.12)

* Be consistent with the units
CSM CUTTING FORCE EQUATIONS

Rolling Force:

\[ F_R = F_N \cdot RC = F_N \cdot Tan \left( \frac{\Phi}{2} \right) = F_N \cdot \sqrt{\frac{P}{D}} \]

Where: 
- \( F_R \) = Rolling Force (kN or lbs)
- RC = Rolling Coefficient
- D = Disc Diameter
- P = Penetration (in)
- \( \Phi \) = Angle of the Contact Area (Rad)
- FN = Normal Force

TBM ROTATIONAL SPEED

- Find the Rotational Speed from the disc max. velocity as:

\[ RPM = \frac{V_{\text{max}}}{\pi \cdot D_{\text{TBM}}} \]

- Or in general use the following Graph (NTH 1-94)
DISC CUTTERS

- Disc cutters available in the market

<table>
<thead>
<tr>
<th>Cutter Diameter mm (in)</th>
<th>Design Bearing Capacity/Max Load Ton (lbs)</th>
<th>Average Cutter Load For TBM Thrust Ton (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 (14)</td>
<td>18 (35,000)</td>
<td>15 (30,000)</td>
</tr>
<tr>
<td>380 (15.5)</td>
<td>20 (40,000)</td>
<td>18 (36,000)</td>
</tr>
<tr>
<td>431 (17)</td>
<td>27 (55,000)</td>
<td>24 (48,000)</td>
</tr>
<tr>
<td>456 (18)</td>
<td>30 (60,000)</td>
<td>26 (56,000)</td>
</tr>
<tr>
<td>481 (19)</td>
<td>35 (70,000)</td>
<td>30 (60,000)</td>
</tr>
</tbody>
</table>

* The Max/bearing capacity is the allowable force on an individual cutter. Average is the Machine Thrust divided by the Number of cutters. In later case the forces on individual cutters in the face are higher than average.

NUMBER OF CUTTERS

- For the given spacing “S” use:

\[ N_c = \frac{D_{TBM} \cdot 12}{2 \cdot S} + K \]

\( K > 5 \)

- Use the Following graph to check it out:
**MACHINE SPECIFICATIONS**

\[ \text{Thr} = \text{Cutterhead Thrust (lbs)} \quad \text{Thr} = N F_N \]

\[ TQ = \text{Cutterhead Torque (ft/lbs)} \quad TQ = 0.3 N FR D_{TBM} \]

\[ \text{HP} = \text{Cutterhead Power (hp)} \quad \text{HP} = \frac{TQ \times RPM}{5250} \]

\[ \text{HP}^* = \text{Installed power} = \text{HP} / \eta \]

\[ \eta = \text{Mechanical Efficiency (\%)} - 90\% \text{ for electric drives} \]

Machine power in KW = \text{HP}^* x

\[ \text{ROP} = \text{Rate of Penetration} \quad ROP = p \times RPM \]

**TBM PERFORMANCE**

![Graph showing TBM performance vs. Uaxial Compressive Strength (MPa)]
GEOLOGICAL CROSS SECTION

Dividing the tunnel into separate reach/segments based on the geology and design features (i.e. turns, slope, support design…)

ESTIMATION OF MACHINE UTILIZATION
**TBM UTILIZATION PREDICTION**

- Ranges from 5-55%, but typically 20-30% range
- Existing models
  - CSM Model
  - NTNU Model
- These models are rarely used
- They indicate the upper bound
- Most studies have shown that neither models have the sensitivity to many input parameters
- It is difficult to predict since in addition to technical issues, it is heavily impacted by site management, experience, human factor . . .

**CONDITIONS AFFECTING TBM UTILIZATION**

- Machine breakdowns
- Site management
- Muck haulage
- Adverse geologic conditions
- Open TBMs
  - Bad / Jointed Ground
  - Double Shields
  - Face collapse
  - Squeezing ground
- Excessive water inflow
- Release of gases (methane, H2S, etc)
## TYPICAL TBM UTILIZATION

- Common ranges for given conditions, Straight tunnels,

<table>
<thead>
<tr>
<th>Machine Type</th>
<th>Ground Conditions</th>
<th>Muck Haulage</th>
<th>Suggested Utilization Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Open</strong></td>
<td>Simple / Consistent or Uniform</td>
<td>Train / Conveyor</td>
<td>35-40% / 40-45%</td>
</tr>
<tr>
<td></td>
<td>Complex / Faults</td>
<td>Train / Conveyor</td>
<td>15-20% / 20-25%</td>
</tr>
<tr>
<td><strong>Single Shield</strong></td>
<td>Simple / Consistent or Uniform</td>
<td>Train / Conveyor</td>
<td>20-25% / 25-30%</td>
</tr>
<tr>
<td></td>
<td>Complex / Faults</td>
<td>Train / Conveyor</td>
<td>15-20% / 20-25%</td>
</tr>
<tr>
<td><strong>Double Shield</strong></td>
<td>Simple / Consistent or Uniform</td>
<td>Train / Conveyor</td>
<td>25-30% / 30-35%</td>
</tr>
<tr>
<td></td>
<td>Complex / Faults</td>
<td>Train / Conveyor</td>
<td>20-25% / 25-30%</td>
</tr>
</tbody>
</table>

- Adjustments only applied to related sections
  - Initial **Learning Curve** 3-5% deduction for first 3-4 weeks
  - For **Turns**, reduce by 3-5% depending on the radius
  - For **grade** other than ~1%, reduce utilization by 2% per 1% increase in grade
  - Contractor **Experience**, up to 10% deduction based on experience, from good (zero deduction) to poor and inexperienced crew (-10% deduction)
  - **Mixed face** conditions 5-10% deduction depending on severity

- Recalculate the cumulative utilization based on combination of these adjustments applied to each section
ALTERNATIVE WAYS FOR TBM UTILIZATION
CALCS

Use time components

\[ U = \frac{T_b}{T_b + T_{tbm} + T_{bh} + T_v + T_{im} + T_{sw} + T_o + T_{tr} + \ldots} \]

- \( T_b = 1000/PR \) (hr/km)
- Other components from the table and graphs

<table>
<thead>
<tr>
<th>No.</th>
<th>Category</th>
<th>Name</th>
<th>Definition</th>
<th>Suggested Formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TBM</td>
<td>Tb</td>
<td>TBM breakdown times</td>
<td>See Figure 7</td>
</tr>
<tr>
<td>2</td>
<td>BC, Tbc</td>
<td>Tbc</td>
<td>Break-up breakdown times</td>
<td>See Figure 8</td>
</tr>
<tr>
<td>3</td>
<td>Cutter, Tc</td>
<td>Tc</td>
<td>Cutter change time</td>
<td>See Figure 9</td>
</tr>
<tr>
<td>4</td>
<td>Support, Tg</td>
<td>Tg</td>
<td>Support installation time</td>
<td>Planner</td>
</tr>
<tr>
<td>5</td>
<td>Regrip, Tg</td>
<td>Tg</td>
<td>Regripping time (min)</td>
<td>See Figure 10</td>
</tr>
<tr>
<td>6</td>
<td>Transport, Tr</td>
<td>Tr</td>
<td>Times related to stock transportation and unloading</td>
<td>Condition: Very Good &lt;100, Good 100-300, Normal 300-700, Poor &gt;700</td>
</tr>
<tr>
<td>7</td>
<td>Maintenance, Tm</td>
<td>Tm</td>
<td>Maintenance of cutter head, TBM and Stack-Up</td>
<td>Based on ground conditions</td>
</tr>
<tr>
<td>8</td>
<td>General, Tg1</td>
<td>Tg1</td>
<td>Overtime related to unforeseeable ground conditions, which needs additional support or diverting</td>
<td>See Figure 11</td>
</tr>
<tr>
<td>9</td>
<td>Probe, Tp</td>
<td>Tp</td>
<td>Probing times for ground exploration</td>
<td>On site</td>
</tr>
<tr>
<td>10</td>
<td>Utility, Tu</td>
<td>Tu</td>
<td>Line extension times</td>
<td>On site</td>
</tr>
<tr>
<td>11</td>
<td>Survey, Ts</td>
<td>Ts</td>
<td>Times for changing surveying stations and checking tunnel direction</td>
<td>( Ts = (230000/L (\text{mm}))^2 \times )</td>
</tr>
<tr>
<td>12</td>
<td>Other, Ta</td>
<td>Ta</td>
<td>Unallocated times</td>
<td>Up to 200 km/km for crews with low experience</td>
</tr>
</tbody>
</table>
ALTERNATIVE WAYS FOR TBM UTILIZATION
CALCS

Figure 2. Hard Rock TBM Downtime Components (Left to right, Tc, Tact, and Tsys).

ADVANCE RATE MODELS

Water condition code:
1: Almost dry
2: Water inflow at tunnel affect the tunnel excavation time (or water inflow/tunnel diameter)=1-2
3: High water inflow at face (or water inflow/tunnel diameter)=3-4
4: Water inflow at tunnel face may stop the tunnel excavation
   (Extreme Mining Area, or water inflow/Tunnel >4, or Inlet>10)
Note: water inflow in inflow line and tunnel diameter in σ.
ADVANCE RATE (AR) MODELS

- Various models have been offered
- Based on Rock Mass
  - RMR → RME system by Bieniawski (2007 . . . )
  - Q → Q_{TBM} system by Barton (2000 . . .)
  - Less often used, available formulas seem to be site specific
- Computer Aided
  - Artificial intelligence (AI) models based on Neural Network and Fuzzy Logic
  - Statistical approach (Nelson, Laughton, Abdel-Jalil)
  - Not commonly used due to unavailability of the programs and databases

STOCHASTIC MODELS, SIMULATIONS

- TBM operation is simulated as a production process
  - Linear activities
  - Parallel activities
  - Interdependency
  - Time between breakdowns
  - Time to repair
STOCHASTIC MODELS, SIMULATIONS

- Has great potential in the future
  - For estimation of machine utilization
  - Identification of the choke points
- Capable of taking into account
  - Machine and Back up specs
  - Ground Conditions
  - Special circumstances (i.e. Transportation)
  - Risk management
- Offer a variety of what / if scenarios
STOCHASTIC MODELS, SIMULATIONS

Example: Double Shield machine, various transportation systems

PERFORMANCE PREDICTION IN DIFFICULT GROUNDS

ITA work group (WG) 14 identified difficult conditions

- over 300 MPa,
- RQD <25%,
- water inflow >30 l/sec,
- highly abrasive rocks,
- >20% of alignment in fault,
- squeezing ground where convergence of over 10% of radius is expected.
- mixed face conditions,
- Presence of gases in the rock and encountering methane and H2S

Impacting ROP

Impacting Utilization
PERFORMANCE PREDICTION IN DIFFICULT GROUNDS

- Existing models are for normal / standard working conditions, unable to predict AR for such conditions
- The type/complexity of such conditions are often unknown,
- Even if they are anticipated, severity is not predictable,
- Mitigation methods has to do with
  - Contractor/Crew experience
  - Machine and backup specs
  - Contract incentives
- Limited cases to be used as baseline for prediction

SUMMARY & CONCLUSIONS

- Several models for estimation of ROP and it is recommended to use several parallel methods
- Performance prediction of TBM in variable rock is very tricky and needs to be handled carefully taking into account the joints
- Performance prediction in mixed ground is determined by the hardest formation at the face
- Limited systems for estimation of utilization, AR models still not reliable
- Process simulation models have great potential
- No prediction models for Difficult Ground TBM tunneling
SUMMARY & CONCLUSIONS

- Tunnels are built by men NOT the machines

INTERESTING QUOTE

- "He has no enemies, but is intensely disliked by his friends."
  - Oscar Wilde
THANKS

Questions?