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



Jamal Rostami, PhD, PE
Hadden / Alacer Gold Endowed Chair
Director of Earth Mechanics Institute
Department of Mining Engineering
217 Brown Hall, 1600 Illinois St., Golden, Co 80401.
Rostami@mines.edu

1

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

2

"THANK YOU FOR SENDING ME A COPY OF YOUR BOOK; I'LL WASTE NO TIME READING IT."

Moses Hadas

3

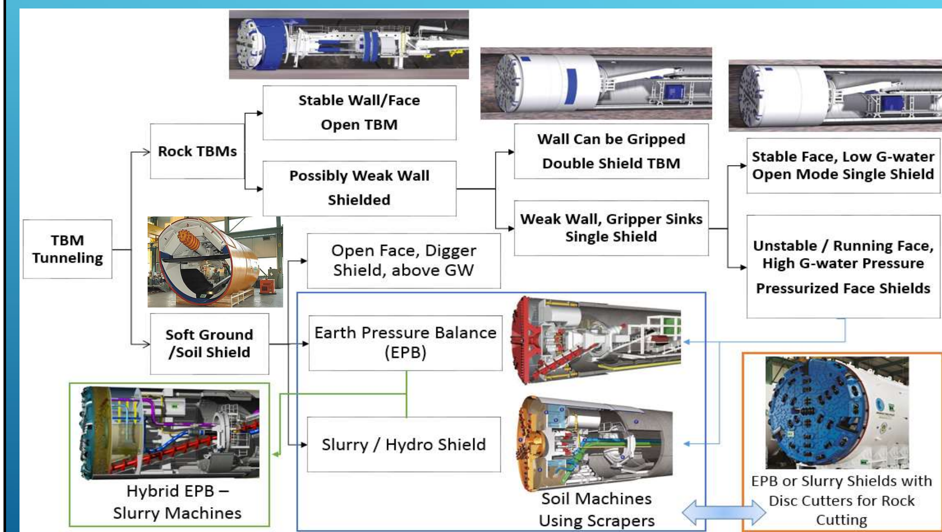
COLORADO SCHOOL OF MINES
EARTH ENERGY ENVIRONMENT

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

4

INTRODUCTION, TBM TYPES



5

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 ot 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 ot ft/hr).
- **IPR**: Instantaneous Production Rate also referred to as Instantaneous Cutting Rate (ICR) is the rate of production while cutting (yd^3/hr or m^3/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)

6

DEFINITIONS

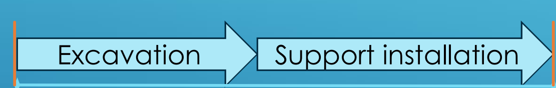
- ROP = Penetration . RPM
- Utilization = $\frac{\text{Excavation Time}}{\text{Total Time}}$
- AR = ROP . Utilization
- IPR = ROP . Face Area

7

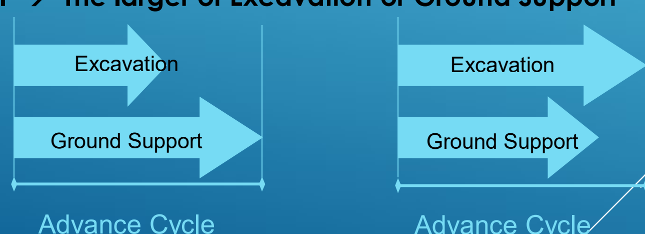
DEFINITIONS

- 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 → Excavation + Ground Support Installation



Double Shield TBMs
Parallel → The larger of Excavation or Ground Support



Open TBM → Mine + regrip

8

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

DEFINITIONS

- **Total Time = Advance Cycles + Down Times**
- **Down Time : Machine Maintenance, Backup System, Utility Installations, Dewatering, Ventilation, Repair, Cutter Change, ...**
- **Working in Linear or Parallel fashion. Meaning performing parallel tasks (i.e. cutter change while performing maintenance or ground support …)**
- **Machine Availability (Typically >80%) =**

$$\frac{\text{Total time - Machine maintenance /repair time}}{\text{Total Time}}$$

9

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

SHIFT TIME BREAKTIME - TBMS

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

10

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

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

Increased Cost & Accuracy

11

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

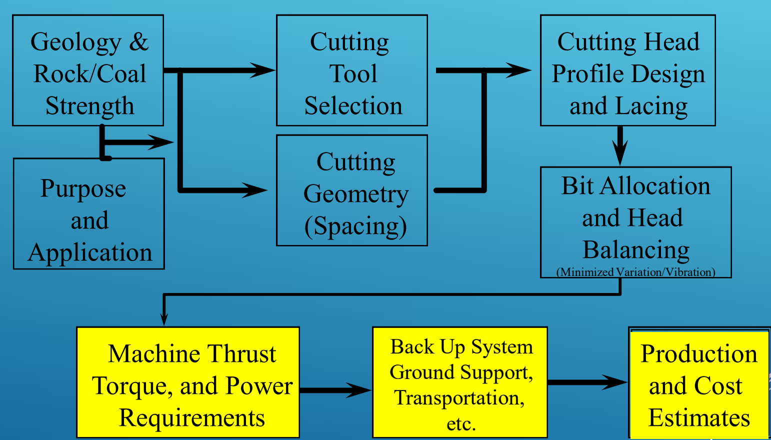
PARAMETERS INFLUENCING MACHINE PERFORMANCE

- Rock Physical Properties
- Rock Mass Properties
- Cutter Type and Geometry
- Cutterhead Design
- Machine Specifications
- Back up System
- Site Planning/Management

12

COLORADOSCHOOLOFMINES EARTH ENERGY ENVIRONMENT

TYPICAL APPROACH TO APPLICATION OF MECHANICAL EXCAVATION SYSTEMS



13

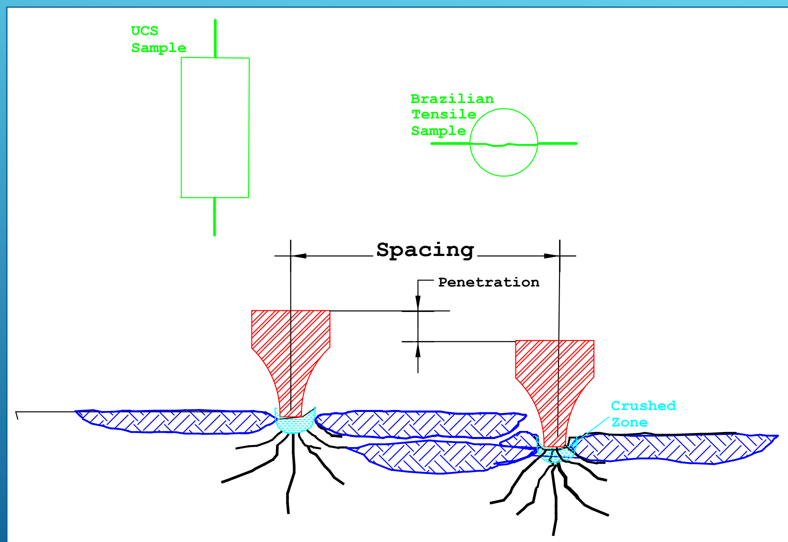
COLORADOSCHOOLOFMINES EARTH ENERGY ENVIRONMENT

COMMONLY USED ROCK PHYSICAL PROPERTY TESTS

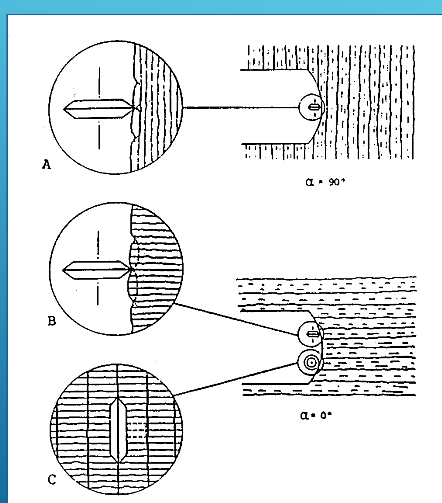
- Uniaxial Compressive Strength (UCS)
- Brazilian (Indirect) Tensile Strength (BTS)
- Punch Penetration Test
- Thin Section Petrographic Analysis
- Cerchar Abrasivity Index (CAI)
- Triaxial Strength
- Acoustic Velocities
- Boreability Index properties
  - DRI, CLI, BWI
  - Total Hardness H_T

14

CHIPPING MECHANISM IN MASSIVE ROCKS



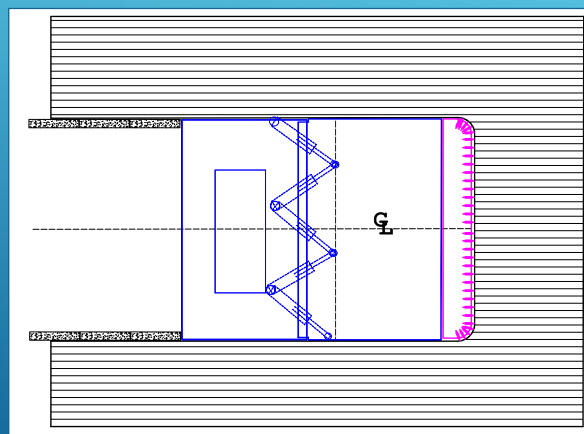
ROCK CHIPPING MECHANISM IN FOLIATED ROCK



(Project Report I-94, Hard Rock Tunnel Boring, University of Trondheim)

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

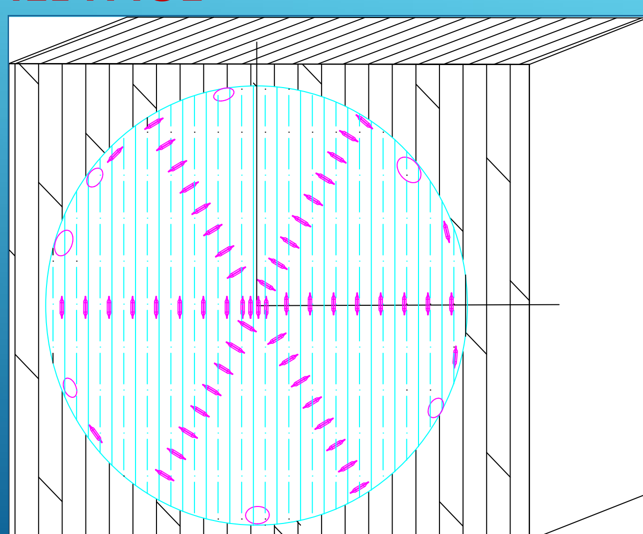
TUNNELING PARALLEL TO BEDDING SIDE VIEW



17

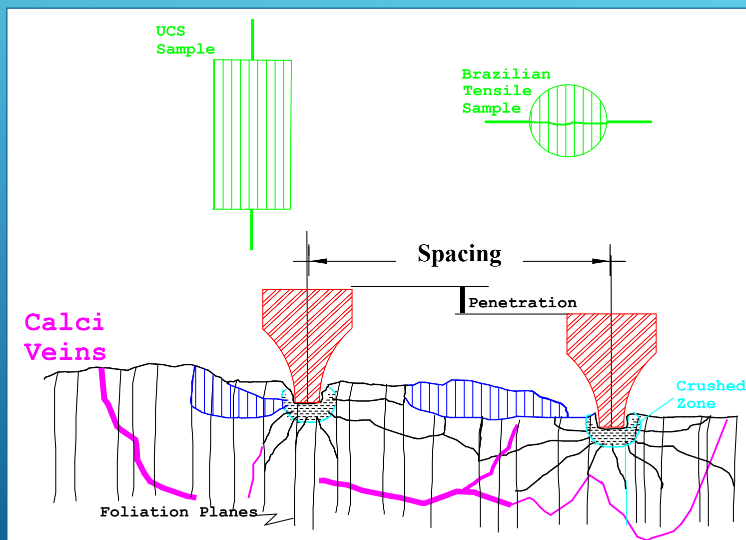
COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

TUNNELING PARALLEL TO BEDDING TUNNEL FACE

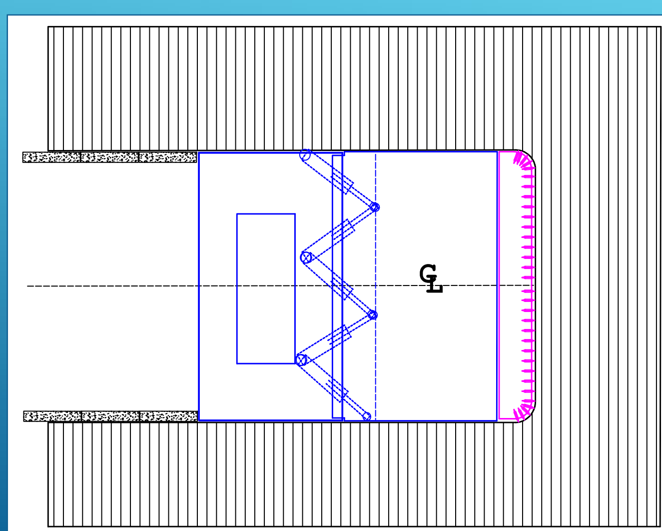


18

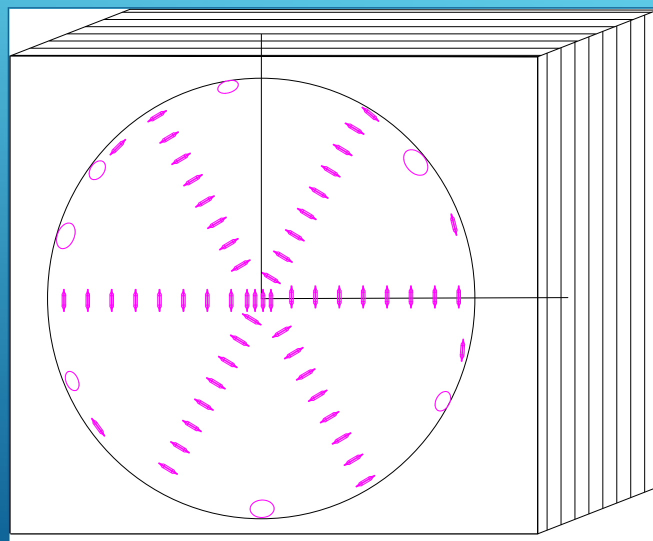
CHIPPING MECHANISM PARALLEL TO BEDDING



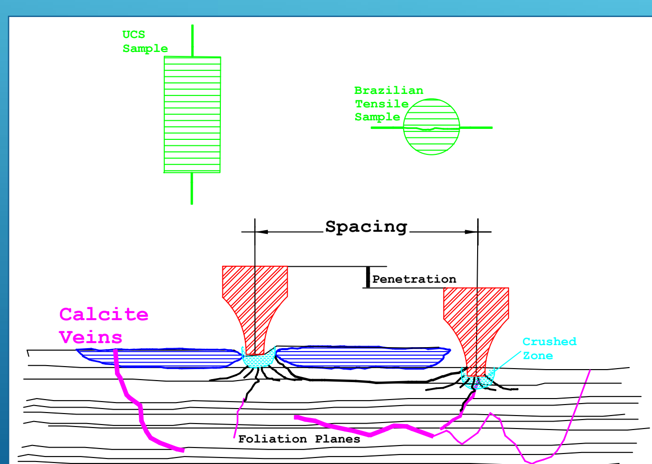
TUNNELING PERPENDICULAR TO BEDDING, SIDE VIEW



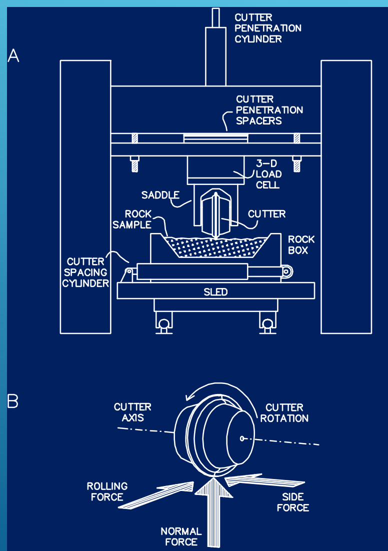
TUNNELING PERPENDICULAR TO BEDDING, TUNNELING FACE

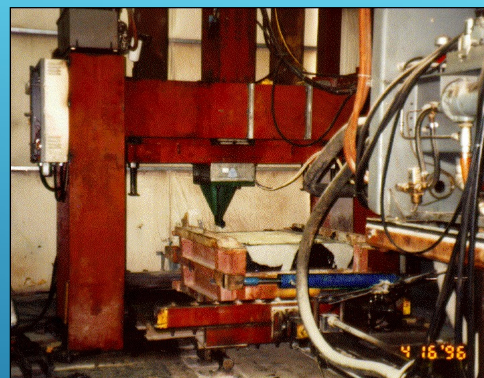


CHIPPING MECHANISM PERPENDICULAR TO BEDDING



LINEAR CUTTING TESTS





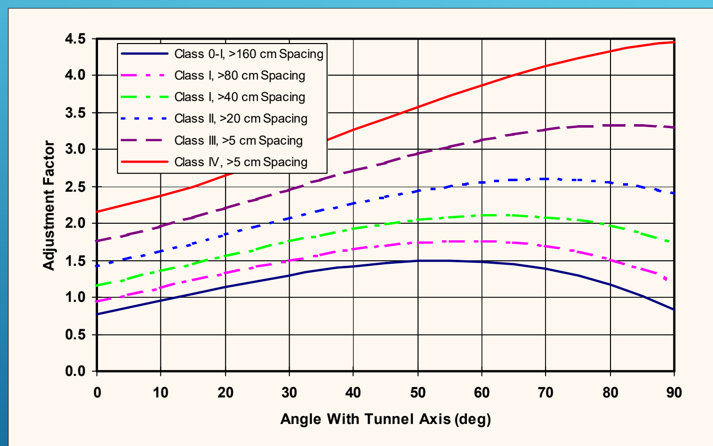
23

ROCK MASS PROPERTIES

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

24

JOINT EFFECTS



(Project Report I-94, Hard Rock Tunnel Boring, University of Trondheim)

25

MACHINE PARAMETERS

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

26

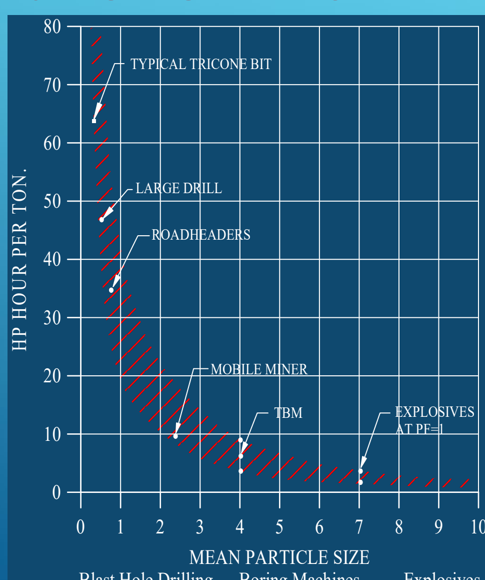
GENERIC METHOD, SPECIFIC ENERGY METHOD

For all types of machines

27

COLORADOSCHOOLOFMINES
EARTH ENERGY ENVIRONMENT

SPECIFIC ENERGY METHOD



$$IPR = \frac{HP.\eta}{SE}$$

IPR = Production Rate (ton/hr)

HP = Machine Power (hp)

η = Mechanical Efficiency (%)

SE = Specific Energy (hp-hr/ton)

$$ROP = \frac{IPR}{A}$$

A=Face Area (m2)

28

TBM PERFORMANCE PREDICTION

29

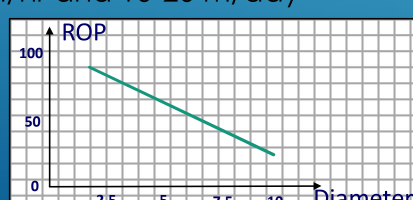
PERFORMANCE PREDICTION OF SHIELDS AND MICROTUNNELING (SOFT GROUND) MACHINES

- 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



30

EXAMPLE OF SOFT GROUND MACHINES

- 20 ft (6 m) diameter EPB,
- Rate of penetration 2.5 in/min (63 mm/min)
- ➔ ROP = 150 in/min = 12.5ft/hr
- Utilization of 20% and 3 shift,24 hr work days
- ➔ Daily advance rate = .2*24*12.5= 60 ft/day
- 5 ft rings = 12 rings /day
- Excavation cycle = 5/12.5 = 0.4 hr=24 minutes
- Lining=segmental lining, 5+1, erected every 20 minutes
- ➔Advance cycle = 24+20 = 44 minutes

31

COLORADOSCHOOLOFMINES
EARTH ENERGY ENVIRONMENT

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 . . .

32

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

33

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

34

- *"He uses statistics as a drunken man uses lamp-posts...for support rather than illumination."*
- **-Andrew Lang (1844-1912)**

INTERESTING QUOTE

35

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

36

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

37

TBM PERFORMANCE PREDICTION

- 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

38

TBM PERFORMANCE PREDICTION

- Nelson's Model,

Input :

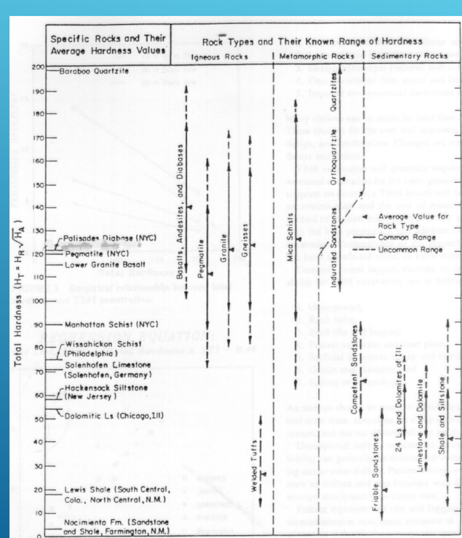
  - Total Hardness
  - Thrust per cutter

Output :

  - Basic penetration,
  - Advance Rate

39

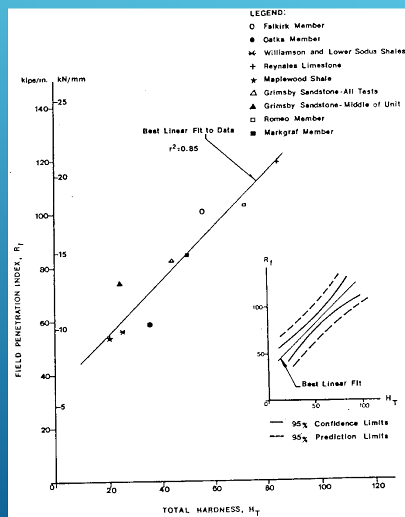
TYPICAL TOTAL HARDNESS OF SELECTED ROCKS



[P.J. Tarkoy 1986]

40

FIELD PENETRATION INDEX (FPI)



$$FPI = \frac{F_n.(kN)}{Penetration.(mm/rev)}$$

(kN/mm/rev)

Prediction,

HT

FPI

Cutter Load

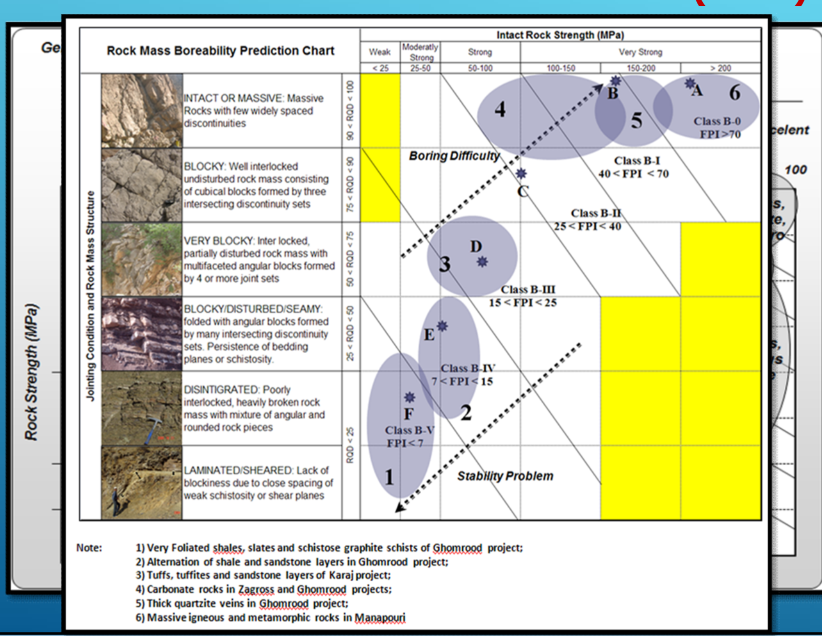
Penetration

ROP=p.RPM

Nelson et. al., 1983

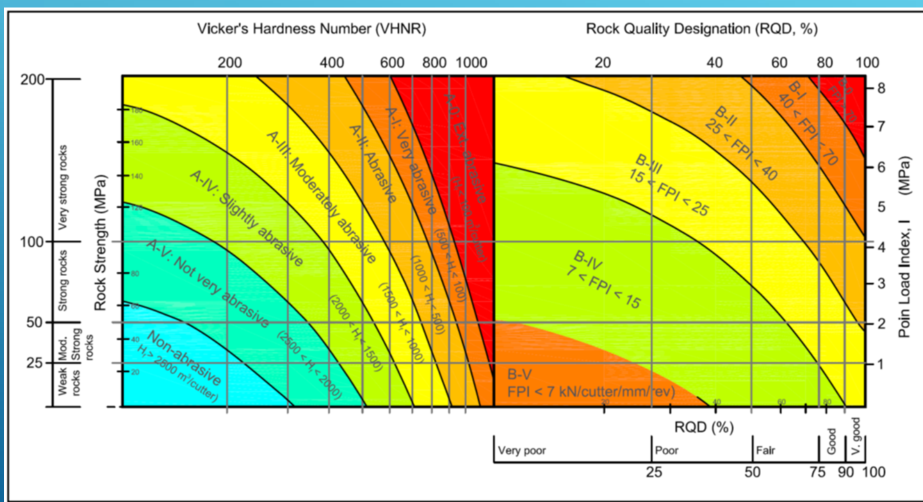
41

UPDATED FPI MODEL BY HASSANPOUR (2009)



42

UPDATED FPI MODEL BY HASSANPOUR (2009)



43

- 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

EXAMPLE

44

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

45

CSM CUTTING FORCE EQUATIONS

Normal Force:

$$F_N = T.R.\Phi.P_r$$

Nominal Crushed Zone Pressure:

$$P_r = C.\sqrt[3]{\frac{S.\sigma_c^{\,2}.\sigma_t}{\Phi.\sqrt{R.T}}}$$

Where: F_N = Normal Force (lbs, kN)

S = Spacing (in, mm)

P = Penetration (in, mm)

σ_t = Tensile Strength (Psi, MPa)

σ_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

46

COLORADOSCHOOLOFMINES

CSM CUTTING FORCE EQUATIONS

Rolling Force:

$$F_R = F_N.RC = F_N.Tan\left(\frac{\Phi}{2}\right) = F_N.\sqrt{\frac{p}{D}}$$

Where: F_R = Rolling Force (kN or lbs)

RC = Rolling Coefficient

D = Disc Diameter

P = Penetration (in)

ϕ = Angle of the Contact Area (Rad)

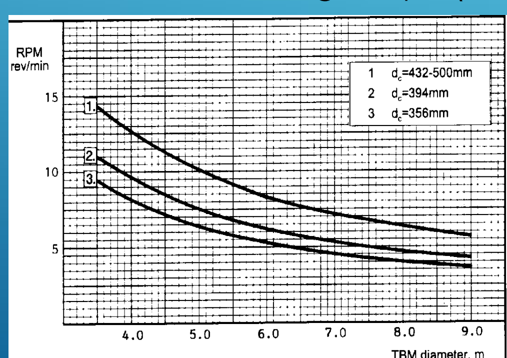
FN = Normal Force

47

COLORADOSCHOOLOFMINES

TBM ROTATIONAL SPEED

- Find the Rotational Speed from the disc max. velocity as: $RPM = \frac{V_{\max}}{\pi.D_{TBM}}$
- Or in general use the following Graph (NTH 1-94)



48

DISC CUTTERS

- Disc cutters available in the market

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

* **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.**

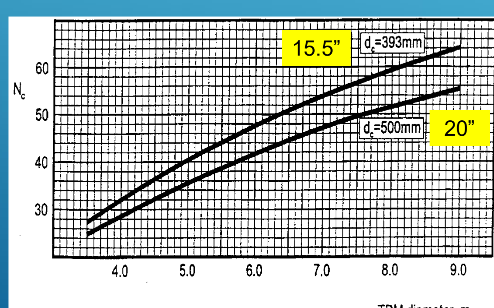
NUMBER OF CUTTERS

- For the given spacing "S" use:

$$N_c = \frac{D_{TBM}.12}{2.S} + K$$

$K > 5$

- Use the Following graph to check it out:



COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

MACHINE SPECIFICATIONS

Thr = Cutterhead Thrust (lbs) $Thr = N.F_N$

TQ = Cutterhead Torque (ft/lbs) $TQ = 0.3N.FR.D_{TBM}$

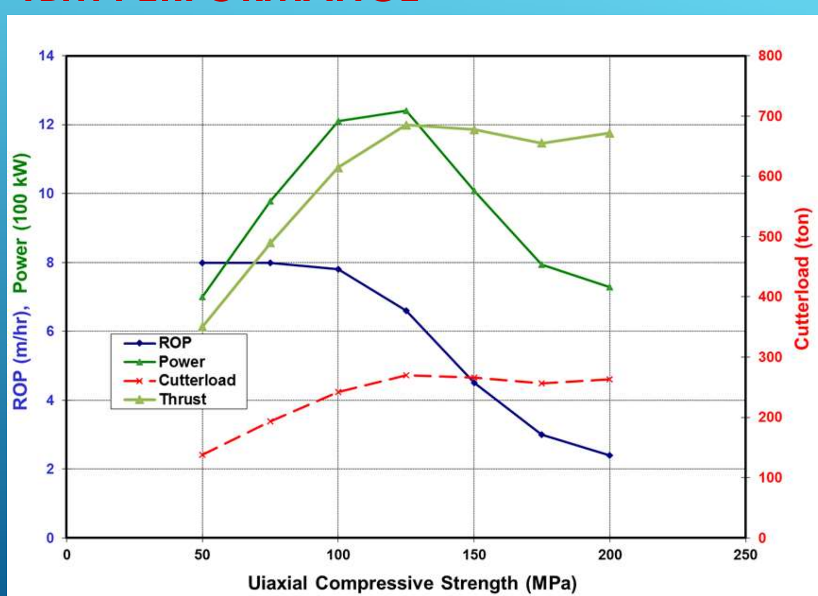
HP = Cutterhead Power (hp) $HP = \frac{TQ.RPM}{5250}$

HP* = Installed power =HP/η
η = Mechanical Efficiency (%) – 90% for electric drives
Machine power in KW = HP* x
ROP = Rate of Penetration → $ROP = p.RPM$

51

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

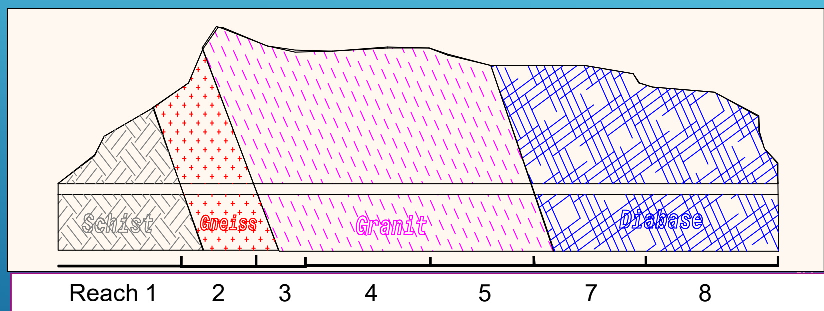
TBM PERFORMANCE



52

GEOLOGICAL CROSS SECTION

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



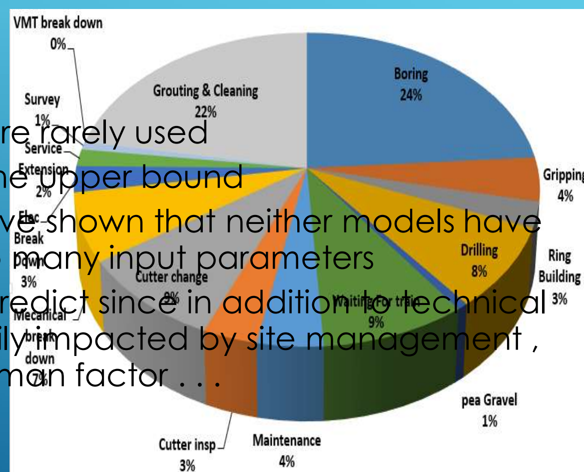
53

ESTIMATION OF MACHINE UTILIZATION

54

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

- Excessive water inflow
- Release of gases (methane, H_2S, etc)

TYPICAL TBM UTILIZATION

- Common ranges for given conditions, Straight tunnels,

Machine Type	Ground Conditions	Muck Haulage	Suggested Utilization Rates
Open	Simple / Consistent or Uniform	Train Contentious / Conveyor	35-40% 40-45%
	Complex / Faults	Train Contentious / Conveyor	15-20% 20-25%
Single Shield	Simple / Consistent or Uniform	Train Contentious / Conveyor	20-25% 25-30%
	Complex / Faults	Train Contentious / Conveyor	15-20% 20-25%
Double Shield	Simple / Consistent or Uniform	Train Contentious / Conveyor	25-30% 30-35%
	Complex / Faults	Train Contentious / Conveyor	20-25% 25-30%

57

TYPICAL TBM UTILIZATION

- 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

58

ALTERNATIVE WAYS FOR TBM UTILIZATION CALCS

- *Use time components*
- $U = \frac{T_b}{T_b + T_{tbm} + T_{bu} + T_c + T_y + T_{sp} + T_w + T_g + T_{tr} + T_r + \ldots}$
-
  - Tb = 1000/PR (hr/km)
  - Other components from the table and graphs

59

ALTERNATIVE WAYS FOR TBM UTILIZATION CALCS

No	Category Name	Definition	Suggested formulas
1	TBM , Ttbm	TBM breakdowns times	See Figure 2
2	BU, T_{bu}	Back-Up breakdowns times	See Figure 2
3	Cutter, T_c	Cutter check/change time	See Figure 2
4	Support, T_{sp}	Support installation time (planned)	See Figure 3
5	Regrip, T_r	Resetting times of TBM after each excavation stroke	$T_r = \frac{1000 \times t_r}{60 \times L_s} + \frac{409000}{R^2}$ L_s is stroke length (m), t_r is regripping time (min) per stroke (2 to 6 min), and R is radius of curves (m).
6	Transport, T_{tr}	Times related to muck transportation and unloading	Condition / Ttr (hr/km) / Comment Very Good / <50 / Tunnel conveyor belt prone to no or very low breakdowns Good / 50 / Belt or Train, low breakdowns Normal / 150 / Belt or Train, normal breakdowns Poor / 350 / High breakdowns (especially in long tunnels) Very Poor / >500 / Trains, very high breakdowns (e.g. simultaneous breakdowns for locos, wagons, and switches)
7	Maintenance , T_m	Routine maintenance of cutter head, TBM, and Back-Up	Based on ground conditions, • Good, Massive soft to medium rock : 50-100 hr/km • Normal, Massive hard rock:100-200 hr/km • Poor: TBM prone to high clogging and high water inflow in poor cementations, presence of expansive clay, very high rock strength for TBM: 300 hr/km
8	Ground, T_g ,T_w	Downtimes related to unfavorable ground conditions, which needs additional or support or dewatering	See Figure 3
9	Probe, T_p	Probing times for ground exploration	Should be estimated based on field conditions
10	Utility, T_u	Line extension times	T_u = 1.3xθ (hr/km) where θ tunnel slope in degree
11	Survey, T_y	Times for changing surveying stations and checking tunnel direction	Ty = 192000/R_2 (hr/km) R = tunnel turning radius (m)
12	Other, T_o	Unclassified times	Up to 200 hr/km for crew with low experience.

60

COLORADO SCHOOL OF MINES

ALTERNATIVE WAYS FOR TBM UTILIZATION CALCS

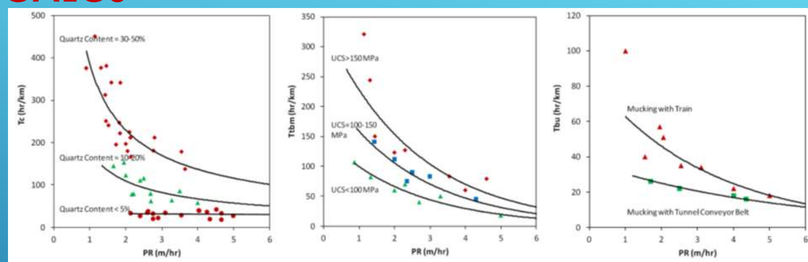
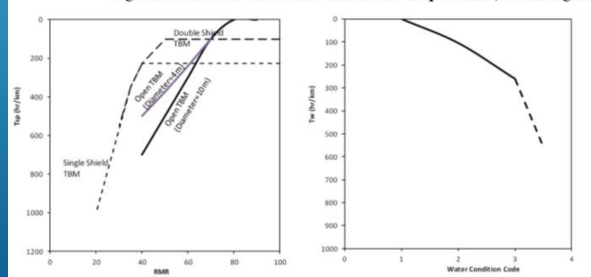


Figure 2. Hard Rock TBM Downtime Components (Left to right, T_c, T_{tbm}, and T_{bu}).



Water condition code:
1: Almost dry
2: Water inflow at tunnel affect the tunnel excavation time (or water inflow/tunnel diameter≈1-3)
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 Diam>10)
Note: water inflow in liter/sec and tunnel diameter in m.

61

ADVANCE RATE MODELS

62

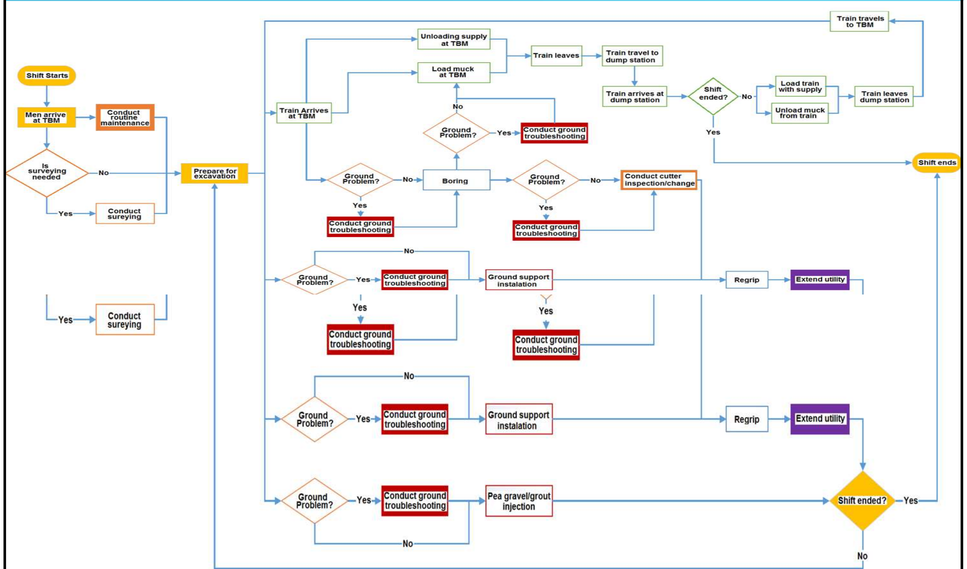
ADVANCE RATE (AR) MODELS

- 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 databses**

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



65

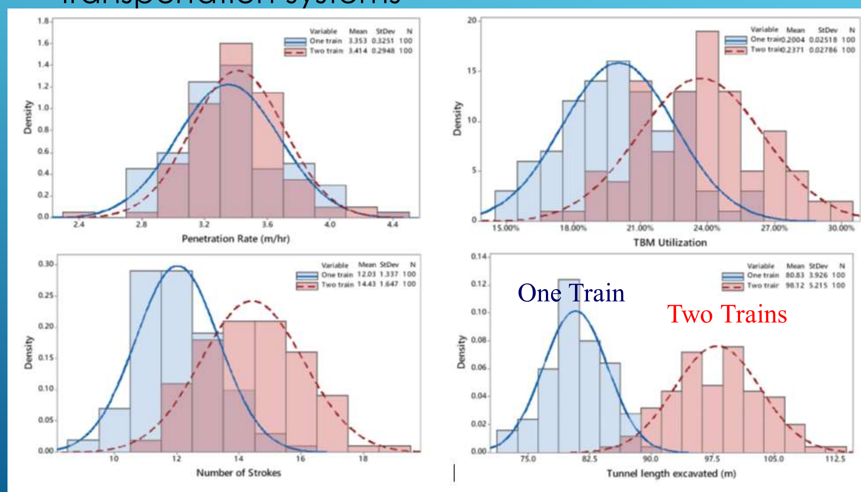
STOCHASTIC MODELS, SIMULATIONS

- 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

66

STOCHASTIC MODELS, SIMULATIONS

- Example: Double Shield machine, various transportation systems



67

PERFORMANCE PREDICTION IN DIFFICULT GROUNDS

- ITA work group (WG) 14 identified difficult conditions
  - **over 300 MPa,** Impacting ROP
  - **RQD <25%,**
  - **water inflow >30 l/sec,** Impacting Utilization
  - **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

68

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**

71

- ***"He has no enemies,***

  but is intensely disliked by his friends."

  - Oscar Wilde

INTERESTING QUOTE

72


THANKS
Questions?
73