Tunnelling and Underground Space Technology 57 (2016) 173–182

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Performance prediction of hard rock Tunnel Boring Machines (TBMs) in difficult ground

Jamal Rostami

Department of Energy and Mineral Engineering, The Pennsylvania State University, State College, PA, USA

ARTICLE INFO

Article history:
Received 15 October 2015
Accepted 11 January 2016
Available online 2 March 2016

Keywords:
Performance prediction
Rate of penetration (ROP)
Advance rate (AR)
Utilization (*U*)
Tunnel Boring Machine (TBM)
Rock tunnelling

ABSTRACT

Performance prediction of TBMs is an essential part of project scheduling and cost estimation. This process involves a good understanding of the complexities in the site geology, machine specification, and site management. Various approaches have been used over the years to estimate TBM performance in a given ground condition, many of them were successful and within an acceptable range, while some missing the actual machine performance by a notable margin. Experience shows that the best approach for TBM performance prediction is to use various models to examine the range of estimated machine penetration and advance rates and choose a rate that best represents the working conditions that is closest to the setting of the model used for the estimation. This allows the engineers to avoid surprises and to identify the parameters that could dominate machine performance in each case. This paper reviews the existing models for performance prediction of TBMs and some of the ongoing research on developing better models for improved accuracy of performance estimate and increasing TBM utilization.

1. Introduction

Ever since Tunnel Boring Machines (TBM) were introduced in 1950s, design engineers and contractors have been preoccupied with the question of accurately estimating machine performance for a given project setting. While much strides have been made in this field for simpler cases of using TBM, recent expansions in the use of these machines in more complex geological settings and concepts of a “Universal Machine” have introduced new sources of complexities and uncertainties. This has led to the use of probabilistic approaches to performance prediction where the advance rate (AR) of a TBM in a given geology is a range, instead of a simple number and the completion time for a project is similarly a range, instead of a certain number of days/weeks, when combining the probabilistic performance of the machine in each segment of a project. The sources of variation in performance of the machine include geological, machine operation, and site management parameters, where each set of parameters follow related histogram of varying input parameters. This approach has been originally used in planning of the Trans-Alpine tunnels in Europe in 1990s (Einstein et al., 1992; Einstein, 2001), and is gradually adopted in other projects as part of the risk management scheme.

In general performance estimation for a TBM refers to estimation of certain parameters which include:

- Rate of penetration (ROP) which is also referred to as penetration rate (PR) and often expressed in m/h and refers to the linear footage of excavation per unit time, when machine engages the ground and is in production.
- Utilization rate (*U*), expressed in percent (%) and representing the ratio of boring time to the total time. Total time could refer to the number of hours worked per work days, boring days, or calendar days.
- Advance rate (AR), which is the amount of daily advance expressed in m/day and is calculated as:

$$\mathrm{AR} = \mathrm{ROP} \cdot U \cdot Ns \cdot Sh, \tag{1}$$

with *Ns* being the number of shifts per day and *Sh* being the number of hours per shift.

Another parameter that is often cited as part of performance prediction is cutter life. This parameter is typically expressed in terms of average cutter life in hours, meter travelled on the face, cutters per meters of tunnel, or cutters per cubic meter of excavated rock. While cutter life is a cost issue and is not directly related to the parameters listed above, TBM experts are expected to offer an estimate for this item. Obviously, increased cutter consumption will impact maintenance time and machine utilization, but this item will not be discussed in current paper. Overall, this paper is not prepared to prove any particular formula/model or be argumentative, rather as an overview of the

---

E-mail address: Rostami@psu.edu

http://dx.doi.org/10.1016/j.tust.2016.01.009

personal experience of the author for over two decades of research on this topic. As such, it will have limited literature survey, calculations, graphs, and tables, instead, it contains highlights of the challenges and opportunities related to TBM performance prediction. Naturally, there would be many that agree or disagree with the points made in the paper and the author would welcome and respect any and all discussions that could help clarify the issues and offer practical solutions to current and upcoming challenges. Following is a brief overview of the various types of machines and methodologies for performance estimation for each category. This will be followed by discussion of models for estimation of ROP and Utilization, and ending with a brief review of challenges related to performance prediction of TBM in difficult grounds.

1.1. Machine types

Various types of TBMs are available in the industry and different systems are used to classify them. Some guidelines for machine selection has been offered by ITA or various tunnelling societies around the world (ITA-AITES, 2000; EFNARC, 2005). But as machines are used in more complex geologies, sometimes there are scenarios where various ground conditions are encountered along the tunnel alignment and as such, clear cut classifications cannot be applied. This is the basis for development of concepts for hybrid machines, which could be between rock and soil machines, as well as shield and gripper TBMs. One can classify machines to soft ground and hard rock. The former machines are always within a shield, protecting the work environment from collapses in the walls and the face. In soft ground, cutting the face is done by drag type tools such as scrapers and normally not an issue. Rock TBMs represent cases where the face comprises rock (full or partial) and requires specialty tools, commonly disc cutters, to break it into manageable size pieces. Meanwhile, one can imagine soft ground machines that have to excavate ground containing boulders or mixed face of soil and rock, while rock machines can run into fault zones filled with gauge and running ground. Thus, complex geological settings and mixed ground conditions require a delicate study of machine selection and related performance issues to balance the cost and risks of operating selected machines in given ground.

That said, TBMs can be classified into two general categories of Open and Shielded machines. Open TBMs are recommended for rock excavation where ground is generally good and stable both at the face and walls. These machines can tolerate some instabilities in the ground and short reaches of unstable ground where special provisions can be used for passing through bad ground. Shielded TBMs are classified as Single or double shield (SS or DS). DS machines have become fairly popular in many rock jobs due to their flexibility to work in good or bad conditions but they are no match to high ground water pressures or water inflow, nor for squeezing grounds. Single shield units are classified into open versus pressurized face machines. Single shields need to push off tunnel linings to propel forward. In dry grounds or grounds where drainage of groundwater can be handled within the tunnels, open face SS TBMs are used. In case of high water pressure at the face or where drainage of groundwater is restricted due to contract requirements, pressurized face machines are used. These TBMs have provisions to remove the excavated muck while maintaining face pressure and preventing water from being removed from the ground. Two primary methods available today for pressurized shield tunnelling include earth pressure balance (EPB) and slurry systems. One can find machines of each type with scrapers or featuring disc cutters for dealing with rock at the face. Fig. 1 is a simple schematic classification of various TBMs used in the industry.

1.2. Basic philosophy of machine performance

Basic concepts for operating TBMs are different between soft ground pressurized face machines and those of open face or rock machines. In soft ground tunnelling, cutting the ground is relatively easy and often not an issue unless rock is present at the face as boulders or as part of the face. The main concern in this soft ground applications is balancing the flow of muck, in particular, assuring that the amount of soil removed from the face is the same as the volume of soil displaced by machine advance. This is to avoid ground settlement due to over-excavation. As such, the penetration rate of the soft ground machines is often fixed to a constant value during the stroke and the flow of muck is closely monitored to maintain face pressure by balancing the volume removed. This fixed rate varies from 100–120 mm/min in small ~3 m diameter to 30–40 mm in large ~15 m diameter TBMs. Even if there is full face of rock to be mined, the volume is often kept constant to maintain ground/water pressure at the face. In such cases, the only item to be checked is the cutterload to make sure that at given penetration rates, the disc cutters are not overloaded. This is a rather simple calculation by estimating the normal force on the disc cutters for penetrating the rock of given properties at estimated penetration per revolution of the head. Thus, estimating ROP of the soft ground machines is based on TBM diameter and prescribed cutting rate, mandated by volume control.

The operation of the rock TBMs are the opposite concept in that the rock at the face needs to be cut and that requires substantial forces on the disc cutters to penetrate the rock. This means that the discs are pressed against the rock to create cutter loads at or below the nominal capacity of the disc cutters or thrust capacity of the machine. This means that the volume of the rock generated is not an issue and most likely can be handled with sufficient number of buckets that can remove the broken material from the face. In other words, most rock TBMs are operated based on force control. The only exception is the softer rocks where the application of high level of thrust and normal force on the discs will result in deep penetration, requiring high rolling forces and cutterhead torque which is beyond the abilities of the machine. In such cases, machine power/torque is used as the controlling parameter for TBM operation. Estimation of ROP in such cases is often based on balance of the forces at the face and not the volume. Obviously, rate of penetration will increase with thrust/cutter load in a given rock and rock mass. The operating point of the machine is where the maximum thrust can be applied before the cutters are over loaded or head jams due to lack of sufficient torque. In such conditions, penetration of the cutters per revolution of the head is estimated and subsequently multiplied by the cutterhead RPM to determine ROP. This allows for maximizing the ROP for a given rock type. The trade-off between the torque-RPM of the head for a given installed power on the machine should also be kept in mind. In harder rock types machine runs thrust limited since higher thrust is needed to achieve little penetration into the face and thus the torque needed to rotate the head is rather small. The excess power available on the machine can then be used in increasing rotational speed (due to constant torque), to maximize rate of penetration. The RPM is limited by the linear velocity of the discs to prevent over-heating of the bearings and is between 165 m/min to 185 m/min for 430 and 480 mm disc cutters, respectively.

To summarize, soft ground machines are operated based on volume control and thus often use constant ROP and rock TBMs are operated at constant thrust and the ROP is constant in a given rock but variable for different rock types. The level of thrust used to operate rock TBMs depend on disc cutter capacity, rock strength, rock mass conditions, and installed machine torque/RPM/power.

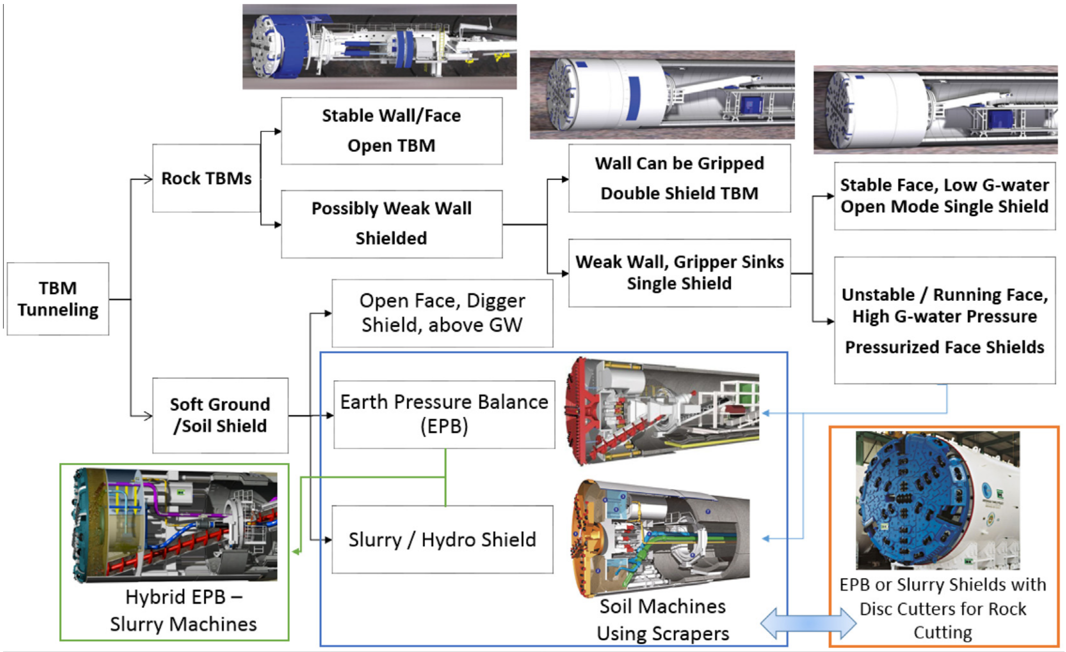


Fig. 1. General classification of TBMs for various ground conditions (pictures from Robbins, Herrenknecht, Tunneltalk).

2. Models for estimating ROP for rock TBMS

There are two camps among researchers when it comes to performance prediction models of hard rock TBMs. One is the force-balance or theoretical approach, and the other empirical models. The first group of models are based on estimation of cutting forces acting on disc cutters and balance of forces between the head and the face. These models are based on the laboratory testing of disc cutters in various rock types and allow for estimation of normal and rolling forces acting on disc cutters while cutting rock of certain strength. The estimated forces are then used to estimate cutterhead torque and thrust and to estimate maximum ROP for a TBM with given specification. The most frequently used model in this group is the Colorado School of Mines (CSM) model. The empirical models allow for estimating the ROP of a TBM of certain size in a rock mass with given characteristics. These models are based on the field observations and analysis of machine performance in past projects. In this category, the most commonly used models are the Norwegian model (NTNU) or Field Penetration Index (FPI) models. Table 1 is a summary of advantages and disadvantages of these modelling concepts.

In each category of modes there are some published works that are somewhat universal, whereas some that are site/rock/cutter-machine specific. The users should be very careful with this issue since the site specific models are often more accurate within the dataset used for their development but very inaccurate with used under different set of parameters. Universal models that were introduced earlier (CSM, NTNU, FPI) may show some deviation in any specific project when compared to recorded field performance of the machine, but they will offer a reasonable prediction when used for new projects. After all, the purpose of modelling is prediction of machine performance, whereas site specific models, in this sense, are based on past performance of a TBM in a project, and they project the recorded AR to estimate the future performance of the machine in the same project. Usually site specific models are developed by contractors and construction management teams for adjustment of original schedule for their tunnelling operations.

A source of common error in modelling and prediction of TM performance is the operating level of a TBM in a given project. This refers to the fact that these models assume that the machine is used to its nominal or full capacity. In reality, there are many precedents where TBMs have been operated under their nominal thrust, cutterload, or torque/power capacity. This creates a notable difference between the predicted and observed rate of penetration when estimating machine performance. The operation of machine under its installed capacities could be due to different reasons. This includes misunderstanding of the machine operating parameters, i.e. misreading of the gages in older machines, and calibration issues with the various instruments, even with the PLC systems on the newer machines. Another reason for this situation is the higher maintenance of the machines when operated at their

Table 1
Advantages/disadvantages of different types of models for performance prediction of rock TBMs.

Model Type	Advantages	Disadvantages
Theoretical	• 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	• 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
Empirical	• 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	• 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

nameplate limits which results in lower utilization and ultimately lower AR. Lack of experience of the operators and contractors with TBMs are also reason for underutilization of the machine. Moreover, machines are operated at lower than their installed capacity when they are negotiating curves or when making alignment correction. This is to minimize damage to the cutters and cutterhead and to assure a smooth transition back to the alignment. Normally, operation manuals provided by manufacturers offer recommended setting for such cases and should be followed to comply with manufacturer's warranty requirements. These conditions should be kept in mind when estimating machine performance.

Empirical models typically include field operation issues and have naturally accounted for aforementioned conditions. However, they cannot predict machine behaviour and speed of cutting when deviating too much from a normal operating condition. Theoretical models can offer better prediction if the operating levels of the machine are known or can be prescribed. Thus they can account for lower thrust and torque applied on the machine and estimate ROP for various machine operating point in a given rock. Theoretical models can be used to modify the predicted rate if the operating thrust level of the machine is known or could be dictated to the operators. These models can also be used for optimizing the use of machine thrust and torque in any given condition. However, anticipation of what the operator will do in the field is sometimes difficult and can create an error in predictions with these models.

The experience shows that in most projects, TBM ROP can be estimated with reasonable degree of accuracy using these models. Obviously 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. The accuracy of the models are fairly good in grounds where the rock is uniform and has lower number of joints or discontinuities. On the contrary, 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. As a result, one of the most complex issues that needs further research is to account for the impact of joints on machine performance, given the nature of rock joints and degree of spatial variability of joints in terms of spacing or frequency, and orientation relative to tunnel axis.

For more detailed discussions on the topic of ROP and related predictive models, one can read the following publications, mainly thesis works in this field. These references offer sufficient details and rather comprehensive coverage of the published material before their completion. Ozdemir (1977) has offered a good overview of the work on theoretical and laboratory based models prior to 1977. Rostami (1991, 1997) offers a follow up on the same type models, followed by the work of Yagiz (2002). On the empirical models using FPI concept, Nelson and O'Rourke (1983) is the initial work and covers the prior studies using the same approach and more recent work by Hassanpour (2009) offers some of the recent updates. Alternatively, the empirical models by Norwegians were discussed in sufficient details by Blindheim (1979) and subsequently in the PhD thesis of Bruland (1998). An excellent compendium of TBM performance prediction models is offered by Gong (2006).

A simple formula that can be used to estimate ROP or PR has been offered by Farrokh (2012). This simple formula can be used for a general or preliminary estimate of machine penetration rate and is as follows:

$$\mathrm{FPI} = \mathrm{Exp}(1.97 + 0.0063 \cdot \mathrm{RQD} + 0.103 \cdot \mathrm{CAI} + 0.00685 \cdot \mathrm{UCS})$$
$$\mathrm{PR} = \frac{0.06\ \mathrm{RPM} \cdot \mathrm{Fn}}{\mathrm{FPI}} \tag{2}$$

where

PR = ROP = Rate of penetration in m/h,
CAI = Cerchar Abrasivity Index,
RPM = Cutter head rotation speed rev/min,
RQD = rock quality designation,
UCS = uniaxial compressive strength in MPa,
Fn = Disc cutter normal force in kN.

One should remember that models based on FPI should check for cutterhead torque limits in rocks below 100 MPa and reduce Fn to assure that machine torque is not exceeded for low FPI values.

3. Estimating TBM utilization

Machine utilization rate is an integral part of TBM performance prediction which reflects the amount of time that the TBM actually excavates rock. The typical utilization rates range from 5% for very difficult and complex geologies with poor site management to around 55% in perfect working conditions for an open type TBM in moderately strong rock with no ground support requirements. However, the most common range of TBM utilization is in 20–30% range. This indicates that machine only work a few hours a day and most of the work time is spent on machine maintenance, repairs, ground support issues, surveying, personnel change over, resolving back up issues, muck transportation delays, etc. These so called downtimes often account for 70–80% of the total time and are usually recorded and analysed in tunnelling projects to evaluate the time distribution for various activities and related delays. Decreasing downtime will have a direct impact on the machine utilization and hence the advance rate, and is the objective of many studies and on site continuous improvements.

While there are plenty of publications discussing machine downtime, delays, utilization, etc., there are only two models that have been offered for prediction of TBM utilization, namely CSM (Sharp and Ozdemir, 1991) and NTNU (Bruland, 1998) models. Both of these models have some shortcomings in that they are first attempt to estimate machine downtimes in given categories but the related formulas are rather old and somewhat insensitive to many of the new machine features and site arrangements. Overview of available machine utilization models and their shortcomings can be found in Farrokh (2012). As a result, TBM utilization models are rarely used for predicting machine utilization tunnelling projects due to low level of accuracy. Part of the lack of success in modelling and prediction of the machine utilization is that utilization factor has an upper bound or limit, but has no lower bound. This means that in some projects where contractor or crew are inexperienced, many seemingly insignificant factors can interrupt the operation and force the machine to stop, resulting in low TBM excavation time, frequent and lengthy downtimes, and very low utilization.

Machine utilization is very sensitive to ground condition. Main part of the sensitivity is related to open type machines where they encounter unstable ground or fault zones and have to install heavy ground support. When shielded machines are used, then bad ground could cause face collapse and cutterhead jamming and affect machine utilization. In deep tunnels, ground convergence and squeezing could become an issue for shielded TBMs, where the ground pressure on the shield can cause entrapment of the shield, which will then require manual release of the machine by hand mining. This is a very risky, time consuming, costly, and dangerous proposition that can cause weeks if not months of delays. Groundwater issues are also a major cause of delays in water bearing formations where the inflow of water can interrupt the operations, and perhaps cause long delays for dewatering/drainage as well as taking extra measures to control water ingress into the tunnel. Presence of gases in the tunnel (i.e. methane, H2S, or other hydro-carbon based gases) is often a serious problem in tunnelling. While the safety issues are often addressed by installing various gas monitoring systems, when gasses are detected, the mitigation measures often are time consuming, cause extended downtimes, and lower TBM utilization. Often measures offered to mitigate the ground related issues, such as probe drilling, cause their own delays and can become source of inaccuracies in predicting machine utilization.

Another source for lack of success in predicting TBM utilization is the impact of human/site related factors. This refers to contractor/crew experience, management style, labour issues, site arrangement, and logistical issues with supplies, repair, and spare parts, electricity and power supply, transportation and site access issues that could limited muck haulage due to special city/site ordinances, availability of local workforce, and so on. The impacts of these factors on machine utilization are often very important but extremely difficult to quantify. Therefore, for prediction purposes, common local practices and available experiences are used to offer an estimate of the machine utilization. Such estimates could be based on modelling, personal experiences, contractor's experience in similar cases, or statistical analysis of machines of similar type/size. However, initial estimates could be adjusted by any of the above factors, if they are known beforehand.

To offer a reasonable machine utilization (*U*) estimate for TBM tunnelling one can start with the values listed in Table 2. The range of values offered for each category reflects author's personal experience for straight tunnels and assuming the skills of reasonably good contractor with relevant experience. Adjustments for the suggested rates can be made for surveying by reduction in offered values in the table by 3–5% for wide and tight radius curves, respectively. If the tunnel is in slopes higher than normal <1%, a 2% reduction for every 1% of slope may be considered. This reflects the slowdown in the process due to transportation and water/drainage issues (i.e. a 3% slope causes a 6% reduction in *U*). Contractor/crew experience and its impact on machine utilization has been discussed in some of the previous studies (Bieniawski et al., 2007, 2008), however, this is a very difficult parameter to evaluate, but overall the lack of experience can reduce the overall utilization by about 10%. Mixed face conditions can reduce utilization by 5–10%. One must keep in mind that the ranges offered in this table should not be applied to the entire tunnel, rather the alignment should be broken into certain reaches and for each section of the alignment, a value for *U* is assigned and the overall utilization rate of the tunnel will then be based on the geometry, curvature, slope, etc. and length of each section, that determines the project based machine utilization. The reductions can be compounded (multiple reductions if the said conditions exist on a given section of the tunnel). The selection of the machine type can also be done based on the utilization rates. As one can observe, the use of open machine in a tunnel with extended reaches of unstable ground with faults will result in lower overall utilization and a shielded machine will be more suitable. Alternatively, in a project where a short length of tunnel might be in fault or shear zone, use of open machine could be justified.

Table 2
General guidelines for estimation of TBM utilization.

Machine type	Ground conditions	Muck haulage	Suggested utilization rates (%)
Open	Simple/consistent or uniform	Train	35–40
		Contentious/conveyor	40–45
	Complex/faults	Train	15–20
		Contentious/conveyor	20–25
Single Shield	Simple/consistent or uniform	Train	20–25
		Contentious/conveyor	25–30
	Complex/faults	Train	15–20
		Contentious/conveyor	20–25
Double Shield	Simple/consistent or uniform	Train	25–30
		Contentious/conveyor	30–35
	Complex/faults	Train	20–25
		Contentious/conveyor	25–30

Another approach for estimation of machine utilization is to evaluate delay times based on downtimes assigned to various categories of activities. This concept has been used in both CSM and NTNU models where the total time is broken to sub-activities such as boring, regripping, cutter inspection/change, haulage delays, surveying, machine repair, and back up repair. These components are represented by related time spent during the shift and the ratio of time used for boring to the sum of all the time components is the machine utilization. Some of the recent improvements in estimating such downtime components can be found in a thesis work by Farrokh (2012). A list of common machine downtime items can be found in Table 3. To apply this approach, one can estimate PR or ROP from Eq. (2) and then estimate Tb as follows:

$$\mathrm{Tb} = 1000/\mathrm{PR}\ (\mathrm{h/km}) \tag{3}$$

Then *U* can be estimated as:

$$U = \frac{T_b}{T_b + T_{tbm} + T_{bu} + T_c + T_y + T_{sp} + T_w + T_g + T_{tr} + T_r + \ldots} \tag{4}$$

It should be noted that the estimated utilization by this formula can be used in Eq. (1) where a more sophisticated model is used for estimation of ROP or PR. Also, one should use lower utilization factor for the first few weeks of machine operation to account for site set up and learning phase. A good rule of thumb for estimating the duration of learning phase is one week for every m of TBM diameter, and machine utilization is 1/2 of what is estimated for the related sections.

4. Advance rate models

Estimation of advance rate or AR is the ultimate goal of performance prediction for rock TBMs. As such there has been some studies where the data was used to directly estimate AR instead of estimating ROP and *U*. Examples of such studies and models are Q_{TBM}, and RME concepts. Rock Mass Excavability (RME) is an index for predicting boreability of a given rock mass by TBM, based on a classification proposed by Bieniawski et al. (2006). One can use this concept to estimate Average Rate of Advance (ARA) using the formulas offered in Bieniawski et al. (2007, 2008). Similarly, Q_{TBM} is an adoption of an existing rock mass classification, namely Q system, for TBM application by Barton (2000, 2011). Some of the published work in the literature shows the marginal success of both systems in predicting TBM performance in projects that were completed in recent years. Part of the problem could be the mismatch between the site setting of the said projects versus the data used to develop the original models. The low accuracy in some cases can also be attributed to the lack of sufficient input data, or use of judgement in assigning the rating for the classifications that could be different than what the developers had intended. Either way, the use of AR models for prediction of TBM performance is fairly limited, but could be used for cross checking other models.

Computer aided models have also been used for estimation of AR as well. These models are based on the artificial intelligence (AI) methods including fuzzy logic or neural network or their derivatives. One example of such model is the work by Alvarez Grima et al. (2000) which offers estimated AR based on a

Table 3
List of components of downtime for rock TBMs (Farrokh).

No	Category name	Definition	Suggested formulas
1	TBM, T_{tbm}	TBM breakdowns times	See Fig. 2
2	BU, T_{bu}	Back-Up breakdowns times	See Fig. 2
3	Cutter, T_c	Cutter check/change time	See Fig. 2
4	Support, T_{sp}	Support installation time (planned)	See Fig. 3
5	Regrip, T_r	Resetting times of TBM after each excavation stroke	$T_r = \frac{1000\times t_r}{60\times L_s} + \frac{409{,}000}{R^2}$ L_s is stroke length (m), t_r is regripping time (min) per stroke (2–6 min), and R is radius of curves (m)
6	Transport, T_{tr}	Times related to muck transportation and unloading	Condition – T_{tr} (h/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 h/km • Normal, Massive hard rock:100–200 h/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 h/km
8	Ground, T_g, T_w	Downtimes related to unfavorable ground conditions, which needs additional or support or dewatering	See Fig. 3
9	Probe, T_p	Probing times for ground exploration	Should be estimated based on field conditions
10	Utility, T_u	Line extension times	$T_u = 1.3 \times \theta$ (h/km) where θ tunnel slope in degree
11	Survey, T_y	Times for changing surveying stations and checking tunnel direction	$T_y = 192{,}000/R^2$ (h/km) R = tunnel turning radius (m)
12	Other, T_o	Unclassified times	Up to 200 h/km for crew with low experience

Note: Some machine types do not require certain activities (i.e. single shield and 8 and 9).

proprietary program that uses built in databases to estimate TBM performance. These programs are not available to general public to use and tend to draw upon the original data set to make the predictions. As such, they are inapplicable to the projects where the geology or machine setting is notably different than their original database. Another approach to estimation of AR for rock TBMs is the use of statistical analysis and a probability based model which as initially developed by Nelson et al. (1999) and was followed up by Laughton (1998) and Abd Al-Jalil (1998). This system offers an estimate on machine performance based on comparison with machine type, size, and geological setting of cases in a database and related statistical analysis and assigned probability functions. The model cannot offer an estimate outside of the original database and since it has not been updated recently, cannot account for performance of newer machines and complex ground conditions.

5. Process simulation for operating hard rock TBMs

As discussed earlier, there are several different models that can offer a reasonable estimate for rate of penetration for rock TBMs. Yet the available models for estimation of the machine utilization is lagging behind. One of the approaches that can be used to provide a flexible approach to estimation of the TBM utilization while offering capabilities to evaluate the impact of various machine configurations and operational parameters in different geological settings is process simulation. This refers to the use of specially developed software or commercial packages that can simulate the TBM operation in a series of discrete tasks or activities having a pre-defined sequence. For example, a TBM can only operate when the utilities are all extended, machine/back up is maintained and functional, required supplies are at the heading, ground support is advanced, muck haulage is ready to receive the cutting, etc. After a stroke, the machine stops for re-grip and train travels to portal, utilities and support may need advancing and so on for the next stroke. Obviously, some of the activities are linear and should be done in particular sequence, while others can be performed in parallel. When excavation is interrupted by any of these activities, they are registered as downtime and will cause delay. Such activities then will be recorded as delays for calculation of shift/daily utilization. Appendix A is an example of a simplified process simulation diagram.

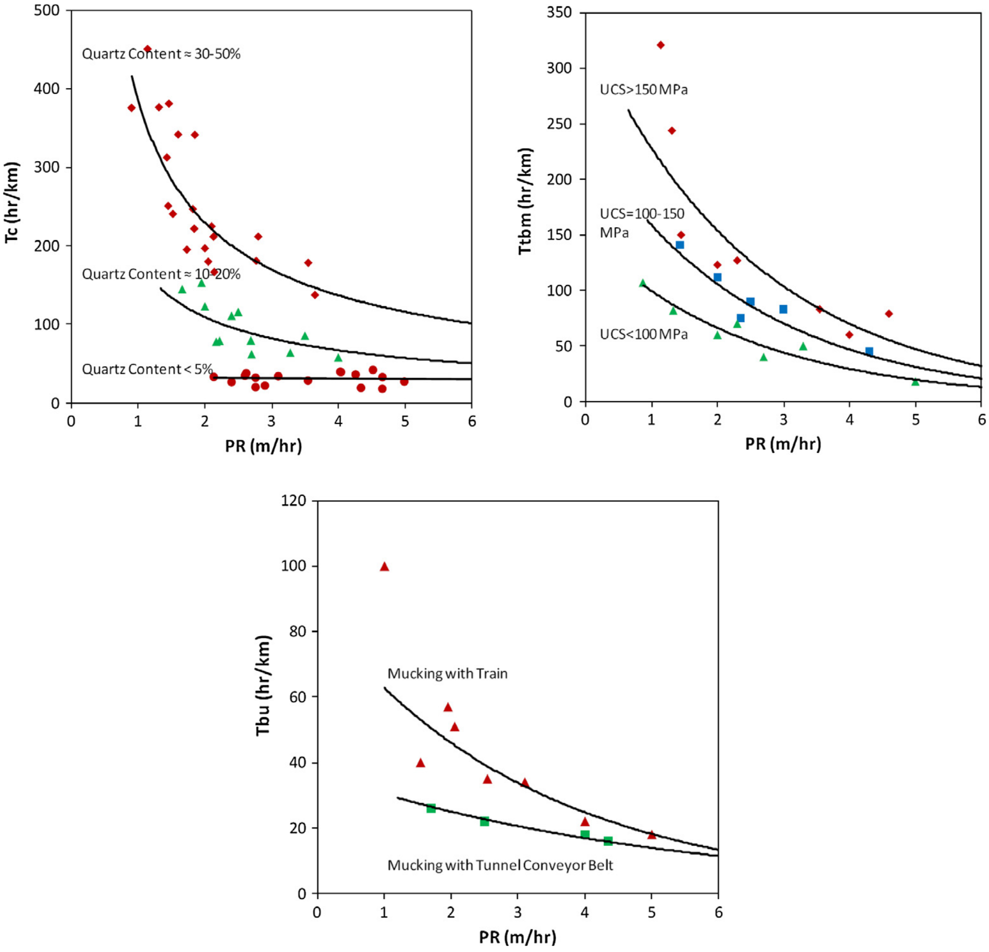
This approach has great potential for developing a model to estimate machine utilization that is based on the actual machine/backup specification and tunnel geology. It can be used as a great tool for systematic risk management, where the impact of various risks on machine performance can be quantified and mitigated by change in tunnel alignment, machine features, operational parameters, site management, and other measures. The model uses probabilistic distribution of time required to complete a task or an activity and can offer a preview of the bottlenecks in operation. The results can help the engineers/owners in the design and planning stage as well as contractors in the bidding/construction stage to reduce and manage the risks, take measures to improve readiness to cope with some of the potential problems, enhance operational efficiency, and improve jobsite safety. The simulation models can also account for resources (equipment, rail, personnel) and allow for optimization of the use of such resources. Fig. 4 shows the results of a preliminary simulation for a Double Shield TBM operation using different number of trains on a job site by the TBM study group at PennState University. The results of simulation can offer a quantitative measure of the impact of various job site configuration and equipment on the overall performance of the machine. This information can help in selection of equipment for a specific jobsite. The results of some of the previous work on this topic can be found in Rostami et al. (2014). Parallel work by the Institute for Tunnelling and Construction Management in Ruhr-University, Bochum under the leadership of Prof. Thewes is published in Duhme et al. (2014).

6. TBM performance estimates in difficult grounds

ITA work group WG-14 on mechanized tunnelling offers a set of criterions for enlisting of challenging projects where mechanized excavation, mostly TBMs, have been used (ITA-AITES, 2009). One can review the list and compare the complexities of the project at hand with the cases listed in this publication. The section that is pertinent to rock tunnelling has listed issues such as rock with strength over 300 MPa, RQD <25%, water inflow >30 l/s, highly abrasive rocks, >20% of alignment in fault, and squeezing ground where convergence of over 10% of radius is expected. This is a partial list of possible difficult ground that a rock TBM can encounter. Obviously projects where extended reaches of tunnel is in mixed face conditions, especially combination of rock and soil or rock and running ground, are very challenging. Presence of gases in the rock and encountering methane and H2S, as in Zogros (Rostami et al., 2010) project in recent years pose a different challenge to the operation.

In general, except for the case where the rock at the face is very hard/strong and extremely low ROP is expected, most other difficult grounds will result in reduced machine utilization when using rock TBMs. This includes weak rock where the ground is unstable and requires additional support and in the case of shield tunnelling, it can lead to face collapse and cutterhead jamming. High depth and in-situ stresses, in combination with the weaker rocks will lead to squeezing conditions where the shield can be entrapped and requires hand mining to release the shield. Squeezing ground can also cause major interruptions in operation of open machines as well due to irregularities in the wall and difficulty in gripping and steering. Frequent joints and blocky ground often show the same symptoms as weak ground when mined by the rock TBM. The added complexity is that sometimes stronger rocks tend to jam into the head, cause frequent disc cutter failures due to impact loading, and extreme wear on the head. Extremely abrasive rocks will wear the cutters at a rapid rate and thus the cutter change time will take a toll on utilization. Often high rock abrasivity coincides with higher rock strength, and this causes very unforgiving conditions for the discs where higher cutter load should be used for penetration, and continued application of high cutter load is the main cause of bearing problems in discs. A failed bearing will lead to flattening of the disc at the face and the ensuing domino effect can cause a full wipe out of the cutters at the face in a very short time, if not detected/intercepted by the operator quickly.

Faults could be water bearing or filled with gauge or mud. When fault zone is filled with weak material, it can intrude the open machines or shielded TBMs operating in open mode (not pressurized face) and cause major setbacks and extended downtimes. High water inflow can cause frequent interruptions in operation as it slows down the transportation, requires frequent installation and maintenance of the pumps and drainage pipes, and if it reaches high enough in the tunnel, it can damage the electrical systems. Similarly, the ingress of hydrocarbon gases such as methane can cause machine shot down if detected early by the gas monitors, and if enough concentration is built can cause explosions. The presence of toxic gases such as H2S requires immediate evaluation of tunnel and shot down of the operation till the



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.

Fig. 2. Hard rock TBM downtime components (Left to right, T_c, T_{tbm}, and T_{bu}).

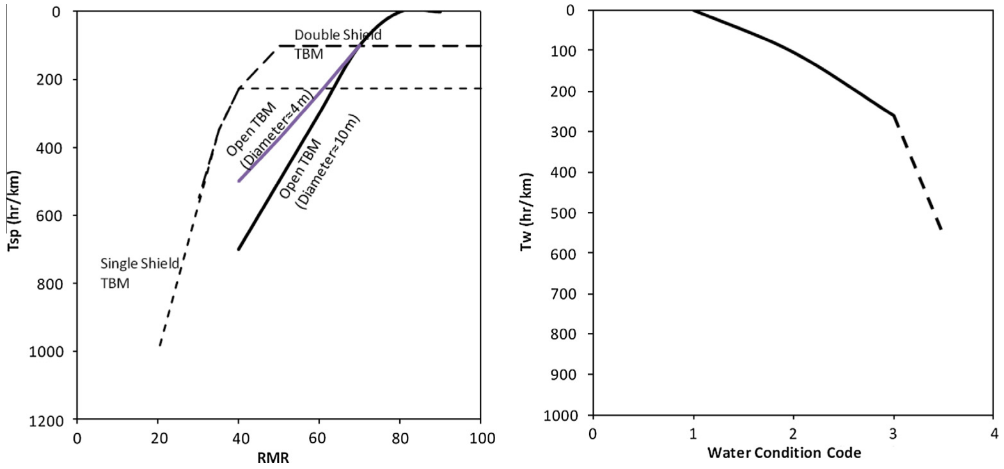


Fig. 3. Hard rock TBM downtime components (Left, T_{sp}, right T_w).

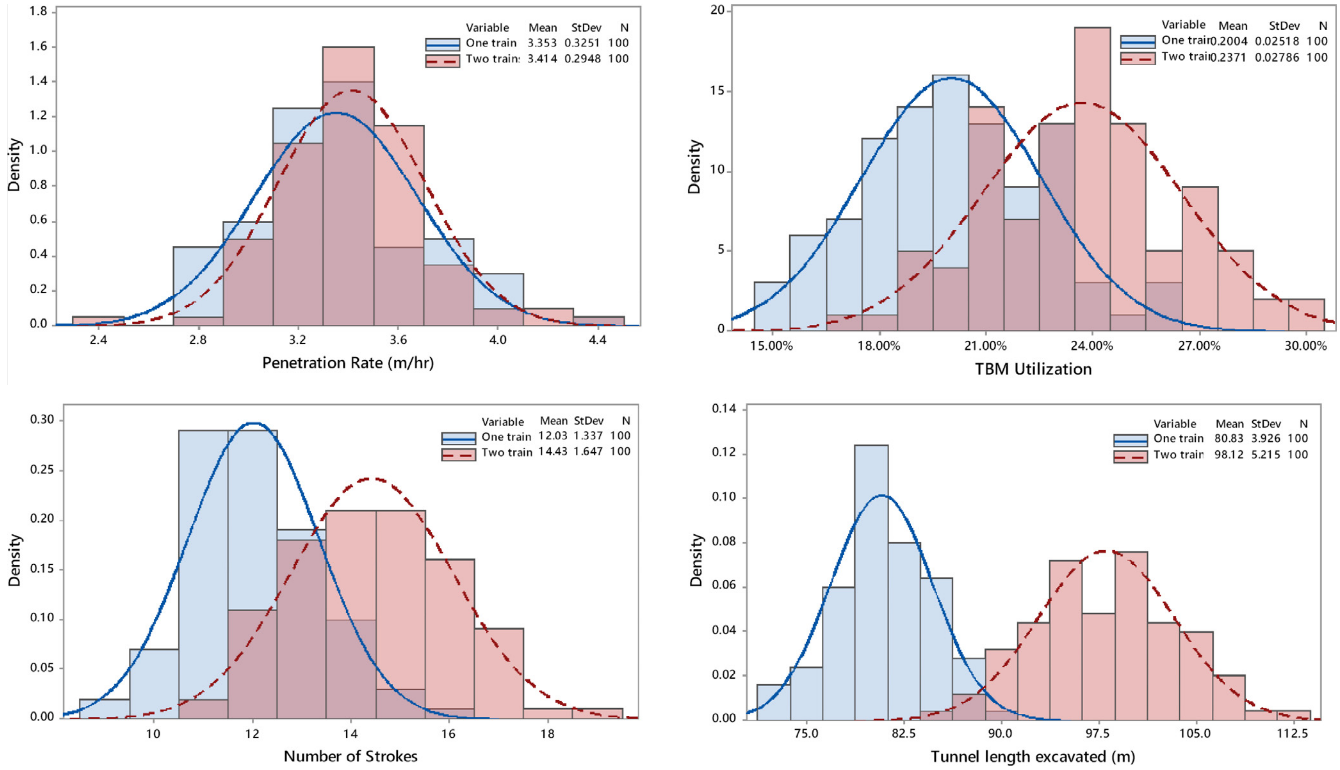


Fig. 4. Preliminary results of simulation for a DS TBM operation using one or two trains for a 24 h period. Estimated tunnel length graph is for simulation of 120 h of operation.

concentration of gases is reduced to an acceptable level. Encountering gases in the tunnel during construction stage when the machine is in the ground but not originally specified for gassy conditions can require major retrofitting and explosion proofing of the machine and back up which could easily take months.

Estimating the performance of a TBM in any of these cases is very difficult if not impossible. When such cases are encountered in a tunnelling project and causes long delays, contractors exclude the related delays and calculate *U* and AR with and without these incidents to see how they fare. In some cases difficult ground is not identified beforehand and as such, the related time and delays are built into the construction claims. Even if they are identified beforehand, the related delays when the machine is actually in such grounds is difficult to predict and estimate since the severity of the conditions could be mistaken or different than what was anticipated due to contractor's means and methods. Ultimately, the time spent on these incidents is directly related to the contractor's experience and contract setting to incentivise the good and efficient performance. A quick look at Figs. 2 and 3 show how difficult it is to estimate machine performance, specially utilization in cases where the rock is very abrasive (thus high T_c), weak (low RMR and low *U*), or flooded (high T_w). It is not unusual to register utilization of zero or in low single digits while TBM is in such grounds and crew is fighting the bad conditions.

To be brief, in many cases these conditions are by no means normal conditions to allow for prediction of TBM performance. In other words, prediction applies to the operations where a reasonable standard procedure can be followed and thus results fall within a manageable range. Operating a rock TBM in difficult ground is impacted by the type and severity of the conditions, capabilities of the machine/backup, skills and creativity of the crew, and site management. There is no known model that can predict the outcome of these site and case specific scenarios.

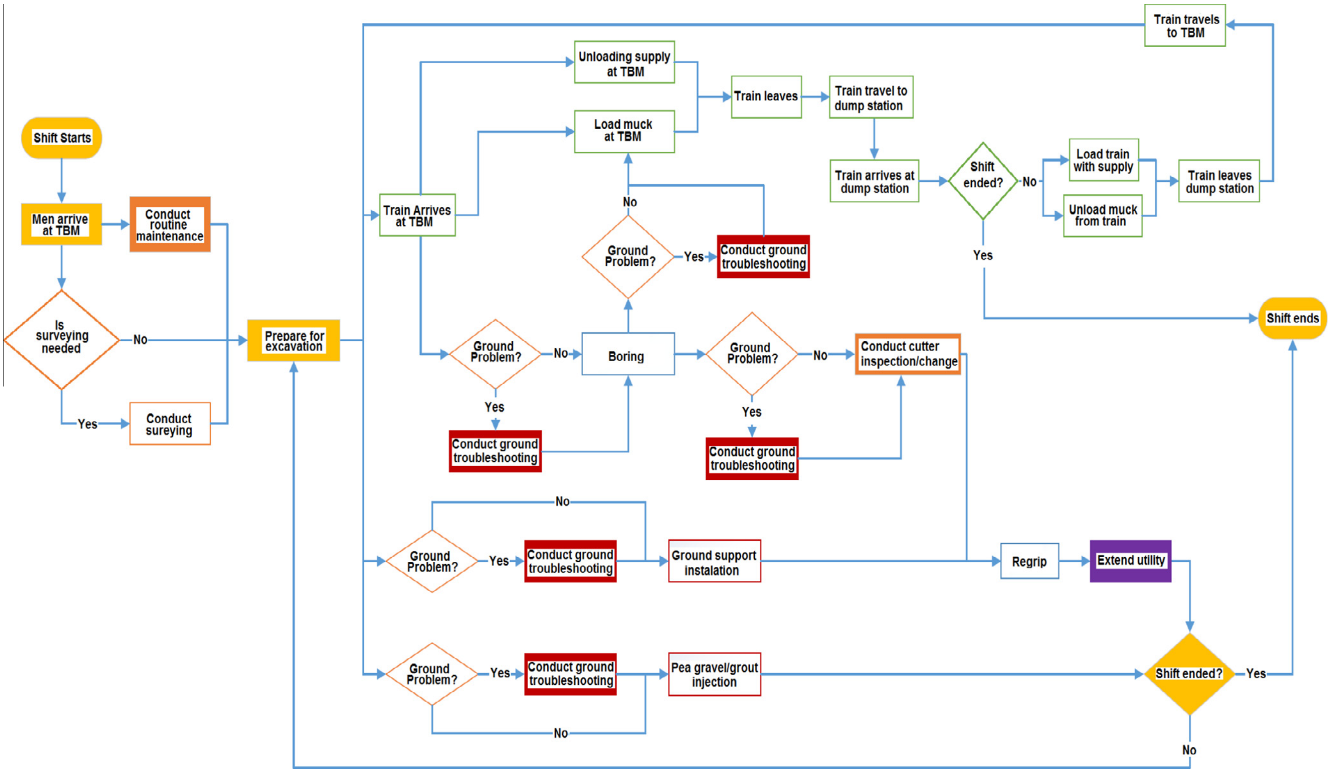
7. Conclusions

As the realm of application of TBMs expand and the industry gradually moves towards the concept of "universal machines", engineers and operators find themselves working on more complex geological settings and difficult ground at higher frequency than before. Predicting machine performance in such scenarios is a very difficult task despite the improvement in understanding of the TBM operation in various conditions and availability of predictive models to estimate machine production rate. There are more options for prediction of ROP than Utilization and AR and the later requires additional focus and systematic analysis of field data for development of flexible and reliable models. This requires cooperation of the industry and contractors to provide machine performance records in various grounds, along with sufficient level of information on ground conditions to the researchers to allow for improvement of existing models and development of reliable models for prediction of TBM utilization. Recent studies on the modelling of the machine operation by process simulation software is very promising for more reliable prediction of machine utilization that will be explored in the future. However, the accuracy of estimating machine performance in difficult ground is still very low due to the high variability of the possible scenarios and means to handle such difficulties.

Acknowledgements

This study has been partially funded by the support from NSF-GOALI under the grant # 1131404. Also the Robbins Company and Frontier Kemper Company have made contributions towards this project. Participation and assistance of Dr. Prescilla Nelson, Dr. Chris Laughton, and Mr. Odd Asklisrud who graciously shared their data with us and efforts of Dr. Ebrahim Farrokh and Dr. Omid Frough is acknowledged and appreciated.

Appendix A. Example of a simplified process simulation diagram for TBM operation



References

Abd Al-Jalil, Y., 1998. Analysis of Performance of Tunnel Boring Machine-based Systems. The University of Texas at Austin, 427 p..

Alvarez Grima, M., Bruines, P.A., Verhoef, P.N.W., 2000. Modeling tunnel boring machine performance by neuro-fuzzy methods. Tunnell. Undergr. Space Technol. 15 (3), 259–269.

Barton, N., 2000. TBM Tunneling in Jointed and Faulted Rock. A.A. Balkema Publishers, Rotterdam.

Barton, N., 2011. TBM prognosis for open-gripper and double-shield machines tunneling through hard jointed rock with weakness zones. In: Proceedings of World Tunneling Congress (WTC), May 20–26, Helsinki, Finland.

Bieniawski, Z.T., Celada, B., Galera, J.M., Álvares, M., 2006. Rock mass excavability (RME) index: a new way to selecting the optimum tunnel construction method. In: Proc. ITA World Tunneling Congress, Seoul.

Bieniawski, Z.T., Celada, B., Galera, J.M., 2007. TBM excavability: prediction and machine–rock interaction. In: Proceedings of the Rapid Excavation and Tunneling Conference (RETC), Toronto, Canada, pp. 1118–1130.

Bieniawski, Z.T., Celada, B., Galera, J.M., Tardáguila, I., 2008. New applications of the excavability index for selection of TBM types and predicting their performance. In: ITA World Tunneling Congress, Agra, India.

Blindheim, O.T., 1979. Boreability Predictions for Tunneling. Ph.D. Thesis. Department of Geological Engineering, The Norwegian Institute of Technology, pp. 406.

Bruland, A., 1998. Hard Rock Tunnel Boring. Doctoral Thesis. Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

Duhme, R., Rahm, T., Scheffer, M., König, M., Thewes, M., 2014. Process simulation as a tool for TBM jobsite logistics planning. In: Proceedings of the Eighth International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground, IS-Seoul 2014, August 25–27, 2014.

Einstein, H.H., Dudt, J.-P., Halabe, V., Descoudres, F., 1992. Decision Aids in Tunneling. Monograph in Conjunction with Research Project for the Swiss Federal Office of Transportation. MIT.

Einstein, H.H., 2001. The decision aids for tunnelling (DAT) – a brief review. Tunnell. Technol. Kor. Tunnell. Assoc. 3, 37–49.

EFNARC, 2005. Specification and Guidelines for the use of Specialist Products for Mechanized Tunnelling (TBM) in Soft Ground and Hard Rock. <http://www.efnarc.org/pdf/TBMGuidelinesApril05.pdf>.

Farrokh, E., 2012. Study of Utilization Factor and Advance Rate of Hard Rock TBMs. PhD Thesis Dissertation. Department of Energy and Minerals Engineering, The Pennsylvania State University.

Gong, Q.M., 2006. Development of a Rock Mass Characteristics Model for TBM Penetration Rate Prediction. PhD Thesis. School of Civil and Environmental Engineering, Nanyang Technical University.

Hassanpour, J., Rostami, J., Khamehchiyan, M., Bruland, A., 2009. Developing new equations for TBM performance prediction in carbonate-argillaceous rocks: a case history of Nowsood water conveyance tunnel. Geomech. Geoeng.: Int. J. 4 (4), 287–297.

ITA-AITES, 2000. Recommendations and Guidelines for Tunnel Boring Machines (TBMs). ITA WG-14 Mechanized Tunnelling. <http://www.ita-aites.org/media/k2/attachments/public/Recommendations_ITA_TBM.pdf>.

ITA-AITES, 2009. Qualification Requirements for Enlistment in Challenging Project List. ITA WG-14 Mechanized Tunnelling. <http://www.ita-aites.org/>.

Laughton, C., 1998. Evaluation and Prediction of Tunnel Boring Machine Performance in Variable Rock Masses. Ph.D. Thesis. The University of Texas, Austin, USA.

Ozdemir, L., 1977. Development of Theoretical Equations for Predicting Tunnel Boreability. Ph.D. Thesis. T-1969. Colorado school of mines, Golden Co.

Nelson, P., O'Rourke, T.D., 1983. Tunnel Boring Machine Performance in Sedimentary Rocks. Report to Goldberg-Zoino Associates of New York, P.C., by School of Civil and Environmental of Civil Engineering. Cornell University. Geotechnical Engineering Report 83-3. Ithaca. New York, pp. 438.

Nelson, P.P., Abad-Aljali, Y., Laughton, C., 1999. Improved strategies for TBM performance prediction and project management. In: RETC, pp. 963–979.

Rostami, J., 1991. Design Optimization, Performance Predictions, and Economic Analysis of TBM Application in the Proposed Yucca Mountain Nuclear Waste Repository. Thesis #4139. Colorado School of Mines, 1991.

Rostami, J., 1997. Development of a Force Estimation Model for Rock Fragmentation with Disc Cutters Through Theoretical Modeling and Physical Measurement of Crushed Zone Pressure. PhD. Thesis Dissertation. Department of Mining Engineering, Colorado School of Mines, T-5008.

Rostami, J., Khademi Hamidi, J., Bayati, M., 2010. Review of TBM utilization and impact of difficult ground conditions in Zagros water conveyance tunnel. In: World Tunneling Conference and 36th general assembly of ITA, May 10–14, Vancouver, Canada.

Rostami, J., Farrokh, E., Laughton, C., Eslambolchi, S.S., 2014. "Advance rate simulation for hard rock TBMs", Korean Society of Civil Engineering. Special edition on tunnelling and underground space construction for sustainable development. KSCE J. Civ. Eng. 18 (3), 837–852.

Sharp, W., Ozdemir, L., 1991. Computer modelling for TBM performance prediction and optimization. Proceedings of the International Symposium on Mine Mechanization and Automation, vol. 1(4). CSM/USBM, pp. 57–66.

Yagiz, S., 2002. Development of Rock Fracture and Brittleness Indices to Quantify the Effects of Rock Mass Features and Toughness in the CSM Model Basic Penetration for Hard Rock Tunneling Machines. PhD Thesis. Dept of Mining Engineering, Colorado School of Mines, T-5605.