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Introducing hard rock TBMs' downtime analysis model with reference to past case histories' data

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Abstract
The study of downtime and subsequently machine utilization in a given project is one of the major requirements of an accurate estimation of TBM performance and daily advance rate. Interestingly, while it is very common to report the components of downtime when discussing a tunneling project in the literature; there has not been a great amount of in-depth studies on this topic in the recent years. This work presents an in-depth analysis of the different components of hard rock TBM tunneling downtime on the basis of the information about several TBM tunneling projects from around the world including some that are underway or completed in the recent years. This includes the comparison of the recorded downtimes with those predicted by the existing models for these tunnels. The results of this comparison show that with the existing models, there is a poor correlation between the predicted and the actual downtime component values. This indicates that the existing models might be outdated or, in some cases, incompatible with the newly developed technologies. In order to provide a more accurate downtime model, an in-depth statistical analysis of the information about the same tunnels, used for the comparative studies, is conducted to develop the new "hard rock TBM downtime model". This model includes a set of formulas and tables as well as some charts to predict different activities' downtimes for three major hard TBM types including open TBM, single-shield TBM, and double-shield TBM. The comparison between the new model predictions and the actual values show a good agreement. The results of this work can be very helpful for the evaluation of time and cost to complete a TBM tunneling project, especially when the downtime is expected to be high.

Keywords: *Tunnel, TBM, Advance rate, TBM Utilization, Downtime.*

1. Introduction

Having a reliable model for prediction of TBM performance is necessary for the estimation of time and cost of completion of a tunneling project, and it is the common objective of several studies in this area. Among the TBM performance parameters (Penetration Rate (PR), Advance Rate (AR), and Utilization (U), etc.), U is one of the hardest parameters to model or predict. There are very few models available for estimation of TBM utilization. The most important of these models, which have guidelines for the estimation of the downtimes and utilization, were developed more than two decades ago by CSM [1] and NTNU (formerly called NTH) [2, 3]. In the recent years, many research works have been conducted by different researchers to evaluate the TBM performance, most specifically, penetration rate (PR) [4-11]. Among these, a few provided new models to predict the TBM utilization factor [12-18]. One reason for the focus on PR prediction may be due to the additional difficulty in modeling the parameters that influence utilization, especially regarding the analysis of different downtimes accumulated over the duration of a TBM drive. Some downtimes such as cutter change are highly correlated with rock properties, while others such as the major TBM system breakdowns cannot be evaluated without knowledge of many parameters such as TBM condition, management, and contractor experience. These parameters are difficult to assess in detail due to the lack of any recent in-depth analyses of TBM utilization and components of system delays. Given the absence of a reliable predictive method for utilization, most researchers and practitioners have continued to use approximate values for it based on reference to TBM field experience under similar conditions.

TBM tunneling is usually performed in a series of cyclic operations, which include several activities. In each excavation cycle, individual activities can cause certain delays, which are usually referred to as the TBM being "down", hence downtime [19]. The TBM performance and daily advance rate depend on the duration of these downtimes. As the proportion of downtimes increases, the performance of TBM decreases. For example, in a weak ground condition, the duration of time spent on ground support installation or ground improvement increases, which results in low utilization, even as low as 10 to 15 percent. Understanding the causes of downtimes is the key to a successful planning of the TBM tunneling and improving machine performance.

In this work, a comprehensive database of 89 tunnel projects from 20 countries is compiled based on the reported downtimes in various publications and contractors' documents. This database is examined to find the most frequent causes of downtime, to evaluate the previous TBM utilization models, and to present a new downtime model (called hard rock TBM downtime model) with a set of formulas, tables, and charts (called hard rock TBM downtime model) for a better prediction of downtime based on project settings and TBM performance parameters.

2. TBM field performance database

The database for the TBM performance and downtime analysis includes 89 tunnel projects from 20 different countries, obtained from published papers and contractor reports. The projects were completed within the previous 30 years with diameters ranging from 2.1 to 11.52 m and tunnel lengths ranging from 134 to 17040 meters. The ground conditions in the database vary from poor to good, and in different rock types, from sedimentary to volcanic. Table 1 and Figure 1 represent descriptive information of the tunnel projects, TBM types, and back-up equipment. A majority of the cases were excavated by the open type TBM, as depicted in Figure 1.

Table 1. Summary of the tunnel projects in the database.

Location	Number of tunnels	TBM Type		
		Open	SS*	DS*
Australia	1	1		
Austria	1	1		
Canada	5	4	1	
China	3	1		2
Ecuador	2			2
Hong Kong	4	2		2
India	1	1		
Iran	4			4
Island	4	4		
Italy	11	8		3
Japan	1	1		
Korea	1	1		
Norway	6	6		
SA	8	8		
Slovenia	2			2
Sweden	3	3		
Switzerland	2	1	1	
Turkey	2		2	
UK	5	5		
USA	23	19	3	1
Total	89	66	7	16

***SS: Single Shield, DS: Double Shield.**

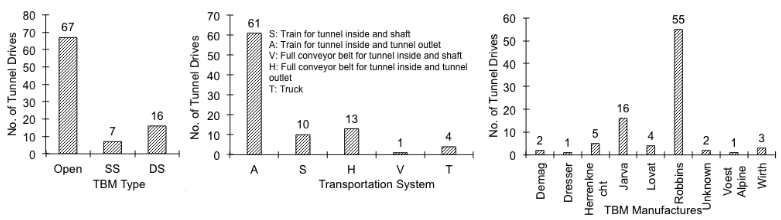

Figure 1. Histograms of different information about the database.

Using different records of the downtimes in the database, the main categories and activities were identified, as listed in Table 2. Downtime associated with each incident is usually reported in percentage of the total shift time. When different categories were reported in the literature, a cross-mapping of the downtime components was applied, where the reported delays were mapped onto the items listed in Table 2 that best matched or described the related activities.

Figure 2 shows the methodology of the calculation of the utilization and advance rate on the basis of the downtime categories explained in Table 2. It should be noted that throughout the entire paper, 'day' refers to a 24-h period disregarding the configuration of its working shifts (e.g. 3*8-h shifts, 2*12-h shifts).

Figure 3 depicts different frequency distribution histograms of downtime items for open type TBM in the database. As it can been seen, most of the distributions are skewed to one side. This makes the subsequent statistical data analysis a bit complex, as this type of distribution forces us to use either data transformation (e.g. Log values) or to divide the dataset into smaller subcategories (the method that is used in Section 5) to reach a more normally distributed frequencies. Without this, the data in the data analysis charts might be highly stacked in just one small area. Figures 4 and 5 present the downtime data in different categories for various projects in the database. It should be noted that different columns in each category refer to different projects. Each color or hatch refers to one project. From these charts, one may find the most probable downtime percentage for the different items explained in Table 2.

Table 2. Downtime categories identified in different tunnel projects.

No.	Category name	Definition
1	TBM, T_{tbm}	TBM breakdowns times
2	BU, T_{bu}	Back-Up breakdowns times
3	Cutter, T_c	Cutter inspection/change time
4	Support, T_{sp}	Support installation time (planned)
5	Regrip, T_r	Resetting times of TBM after each excavation stroke
6	Transport, T_{tr}	Times related to muck transportation and unloading
7	Maintenance, T_m	Routine maintenance of cutter head, TBM, and Back-Up
8	Ground, T_g	Downtimes related to unfavorable ground conditions (additional or supplementary support)
9	Probe, T_p	Probing times for ground exploration
10	Utility, T_u	Line extension times
11	Survey, T_y	Times for changing surveying stations and checking tunnel direction
12	Other, T_o	Unclassified times

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

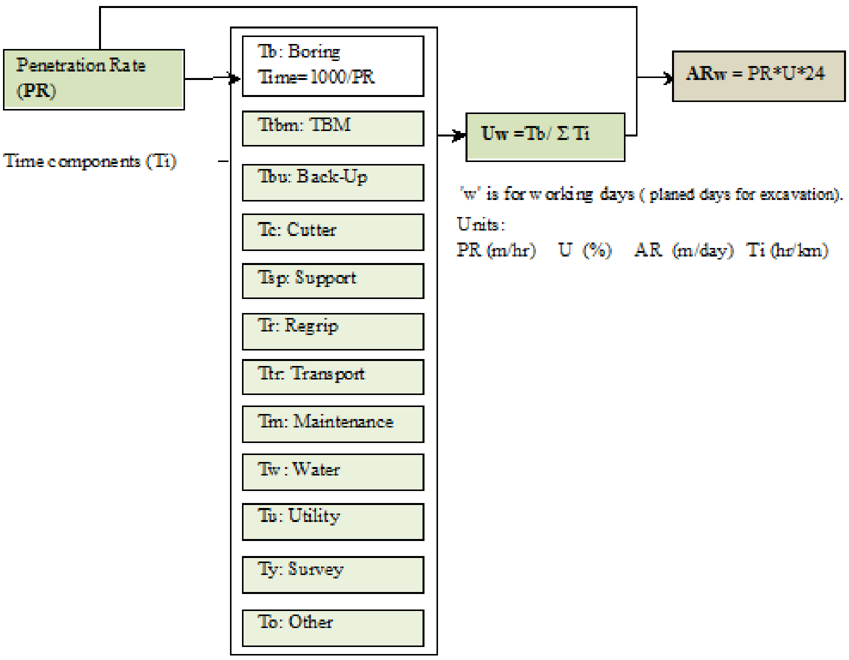

Figure 2. Methodology for advance rate prediction.

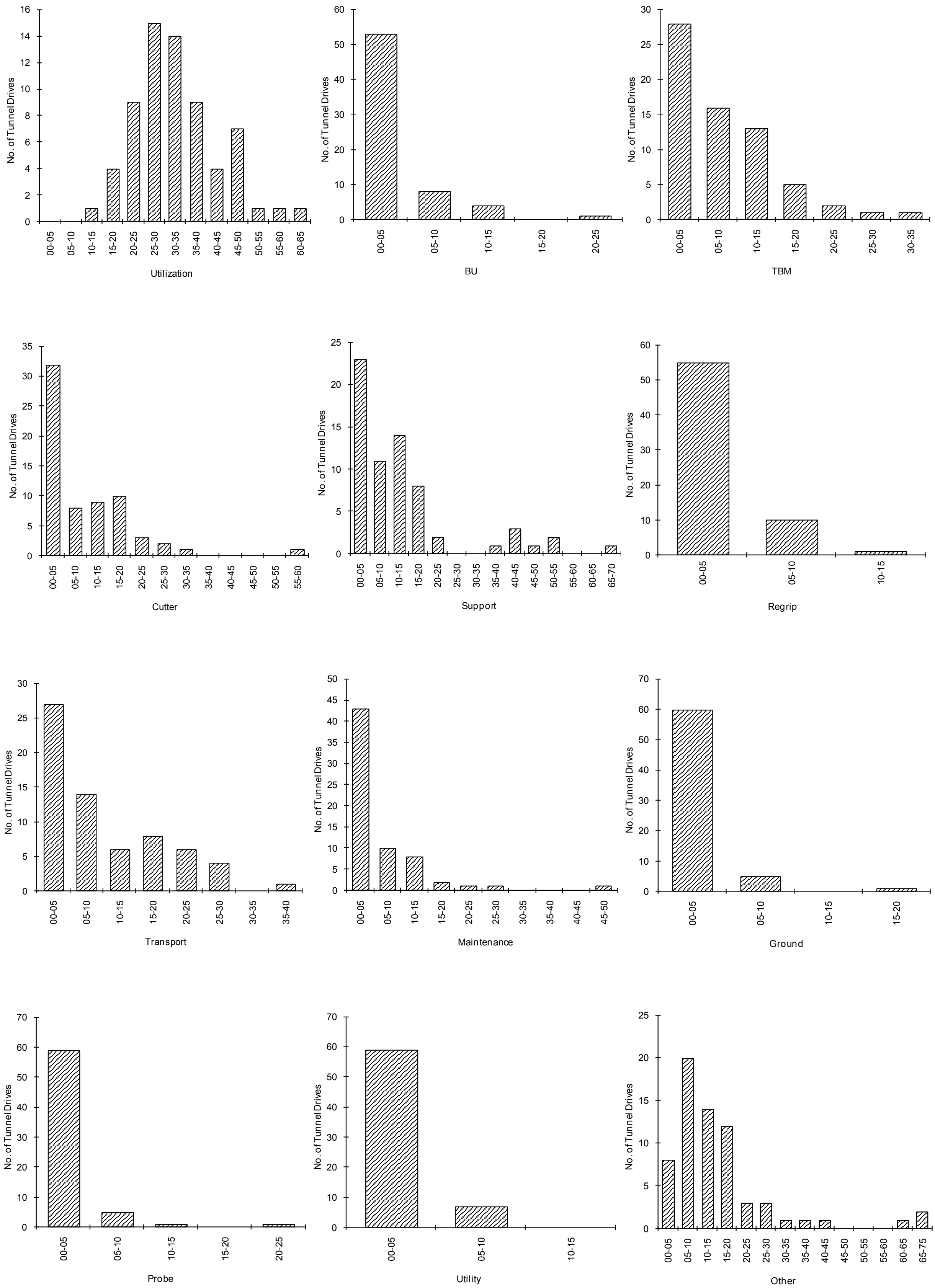

Figure 3. Histograms of allocated time for different activities for Open TBM (in %).

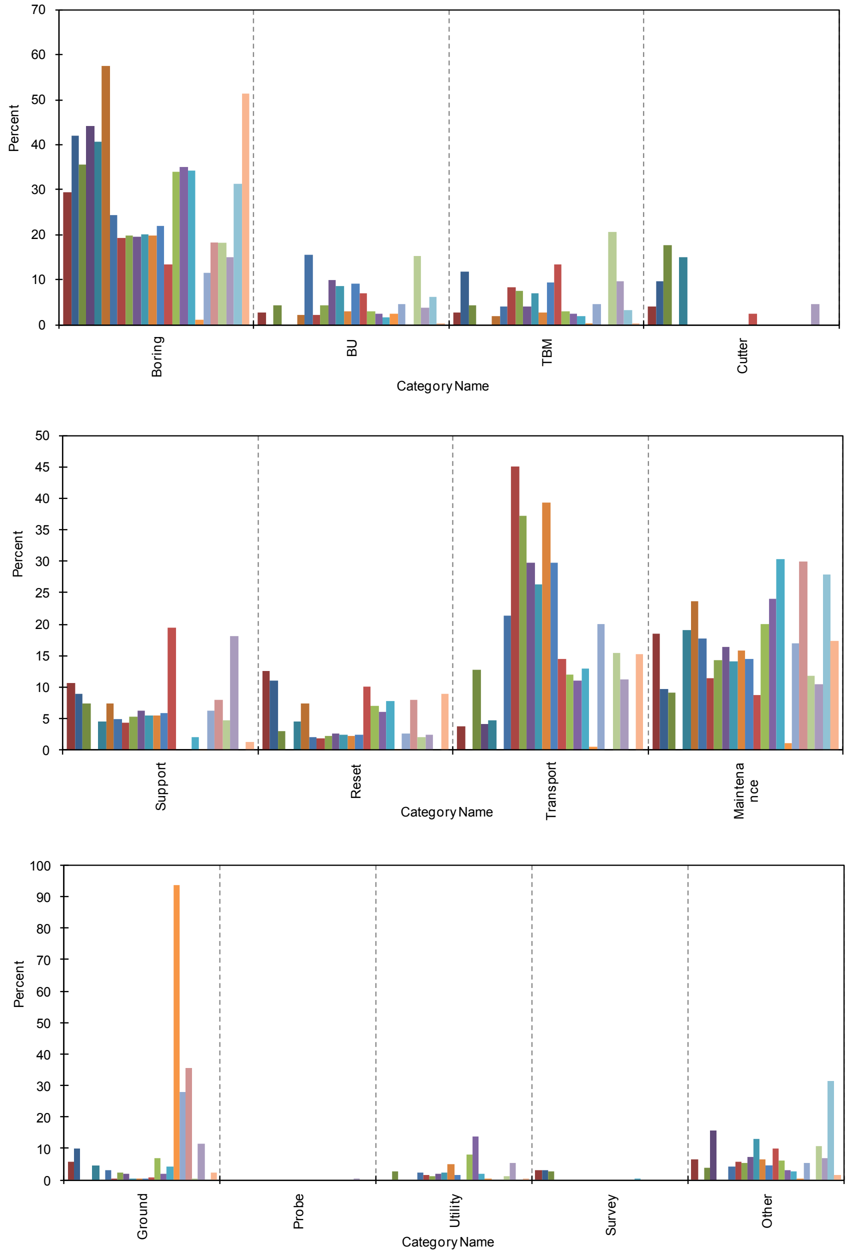

Figure 4. Various allocated times for different activities for Double Shield TBM (in %); different columns in each category refer to different projects.

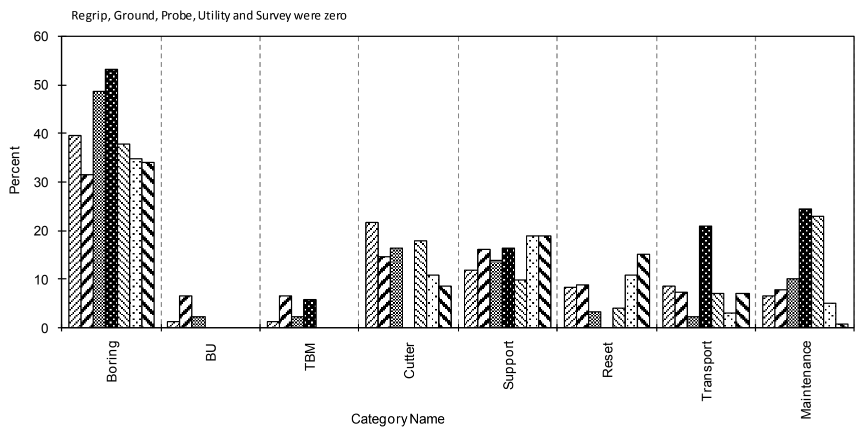

Figure 5. Various allocated times for different activities for Single Shield TBM (in %); different hatches refer to different projects.

3. Total time-controlling process

In reviewing the TBM performance records, there are different approaches that can be used for presenting various parameters. The difference in these approaches is related to the definition of the total time for calculating the Advance Rate (AR) and the Utilization (U). These definitions of the total time are listed as follow:

- Calendar days: Number of days between the start and finish of tunnel project,
- Working days: Number of days planned for working, which is generally total calendar days minus holidays,
- Boring/production days: Number of days in which TBM excavates and advances,
- Available time: This refers to a fraction of boring days in which TBM is available for boring (thus referred to as the machine availability). In other words, the total time of boring days minus the TBM maintenance and other downtimes related to TBM. It should be noted that in some papers "Available time" refers to working days.

The TBM performance parameters AR and U for each one of the above-mentioned categories can be shown as follow:

- Calendar days: ARc, Uc
- Working days: ARw, Uw
- Boring days: ARb, Ub
- Available time: ARa, Ua

One of the main impediments in dealing with the TBM utilization and downtime analysis is that in some literature, the basis for the total time used for the calculation of the TBM parameters is not well-defined. In order to control the compatibility of the gathered information in the database, a procedure was adopted to screen and reorganize the data. In this procedure, the calendar date chart, project holidays, and major stops were used to calculate the different total times and TBM performance parameters explained above. Then the calculated TBM performance parameters were cross-checked with the reported TBM performance parameters in the literature to assign the category of the reported AR and U. The outcomes of this controlling procedure increase the consistency and reliability required for the next set of analysis of operational downtime, AR, and U. It should be noted that in this approach, the assumption is that the reported PR values are the average values for the whole length of a tunnel drive or a geological zone.

Once the appropriate category of the reported AR and U is assigned, it is possible to convert the downtimes from the unit of% to the unit of h/km (Eq. 1).

$$\text{Downtime}\left(\text{h / km}\right) = 1000\ \text{Downtime}\left(\%\right) / \text{AR} / 24 \qquad (1)$$

4. Evaluation of existing utilization models

In this section, the reported downtimes are compared with those predicted by the three utilization models presented by Earth Mechanics Institute (EMI) of the Colorado School of Mines (CSM) [1], the Norwegian Institute of Technology (NTH or NTNU) [2, 3], and Ribacchi and Lembo Fazio [20]. The purpose of the comparisons is to test the predictive capabilities of these models, especially when more recent data is used in the prediction.

4.1. CSM method

The CSM method was based upon the analysis of a specific TBM field database compiled by researchers in mid-1980's to evaluate the TBM utilization and to identify the major parameters and ways to improve or increase the machine advance rate. This approach includes almost all aspects of TBM operations and all activities on a job-site in addition to the ground conditions. In this approach, the delay times associated with machine operations and job-site conditions can be predicted in the unit of hours per tunnel meter (h/m) (Table 3).

Using the equations listed in Table 3 and the reported downtimes for different categories, the predicted values for each downtime item have been calculated and compared with the reported values.

The results of this comparison are shown in Figure 6. It should be noted that the charts only illustrate the reported values and respective predicted values and as such, the number of the points in different graphs are different due to heterogeneity of the available datasets. As it can be seen, for the majority of the cases, the predicted values are lower than the reported ones, and in some cases, the difference is several times the predicted values. This means that in most cases, the model underestimates the downtime of the machine or overestimates the utilization rate. This could most likely be due to the limited database of this model or absence of any recent tunnel projects and improved machine performance due to the technological advances. Furthermore, it seems that the database of this model does not include long delays that are common for some projects.

Table 3. Prediction of TBM utilization using CSM method [1, 21].

Equations	Definition of terms
$U(\%)=\dfrac{T_b}{(T_b+T_r+T_m+T_a+T_{mu})\times f_{10}}\times 100$ $T_m=t_1+t_2$ $t_1=0.067\times T_b$ $t_2=f_4\times T_b$ $T_r=f_3\times L$ $T_a=F(t_s,t_w,t_u,t_p)$ $t_s=(\dfrac{192}{R^2}+0.0033)\times L$ $t_w=f_6\times L$ $t_u=(0.03+0.0013\times\theta)\times L$ $t_p=f_9\times L$	$T_b=$ Time of boring (h); $T_m=$ Time of machine delay; $t_1=$ Scheduled maintenance; $t_2=$ Unscheduled maintenance; $T_r=$ Regrip time; $T_a=$ all system delays; $t_s=$ Surveying delays (h); $t_w=$ Water inflow delays (h); $t_u=$ Utility delays (h); $t_p=$ Support installation (h); $T_{mu}=$ mucking delay (h/m) $\begin{cases} \theta & Mucking-method & Delay \\ Start-up & Truck & 0.115 \\ -15\ \ to\ \ -1 & Conveyor & 0.071\times L \\ -1\ \ to\ \ +3 & Train & 0.056 \\ +3\ \ to\ \ +15 & Conveyor & 0.071 \end{cases}$ $R=$ Radius of curvature of horizontal curves (m); $L=$ Length of tunnel (m); $f_3(hr/m)=0.03(hr/m)+\dfrac{409(m-hr)}{R^2}$ $f_4=\begin{cases} 1\ \ (hr) & start-up \\ 0.324\,(hr) & production-phase \end{cases}$ $f_6=\begin{cases} 0.0056\ (hr/m) & \min imal \\ 0.085\ \ (hr/m) & 3-4m^3/\min/m \\ F(\mu,\theta)(hr/m) & high \end{cases}$ $\mu=$ Water inflow rate; $\theta=$ Tunnel slope (degrees); $f_9=\begin{cases} 0\ \ hr/m\ for\ RMR\ class\ I, II, III \\ 0.028\,hr/m\ for\ RMR\ class\ \ IV \\ 0.043\,hr/m\ for\ RMR\ class\ \ V \end{cases}$ $f_{10}=$ 1.025 (for labor delay)

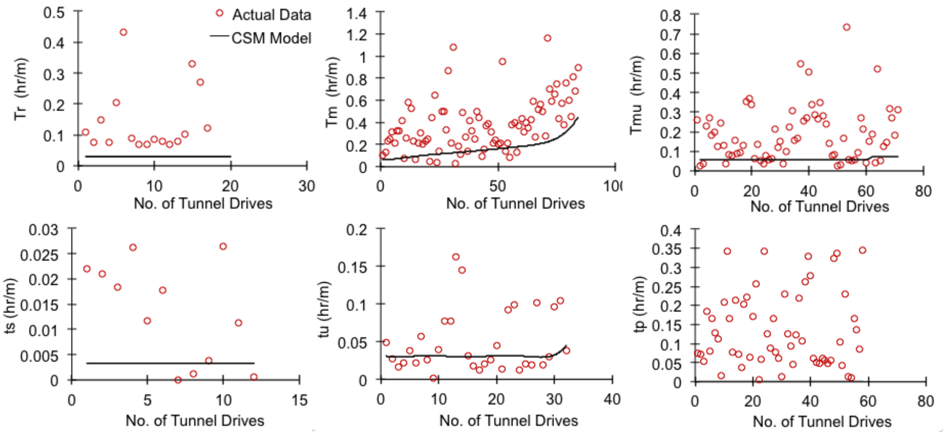

Figure 6. Comparison between reported and predicted values of different time items of CSM model.

4.2. NTNU method

According to the NTNU model [2, 3], in order to predict the TBM utilization, some geological, machine, and operational factors should be taken into consideration. These factors will impact the components of TBM operation and various activities, and the related time includes the mining time, regrip time, cutter change time, TBM/Back-up maintenance time, ground support, and miscellaneous downtimes such as waiting for the empty cars and surveying. The formulas used to calculate the utilization factor are summarized in Table 4. The database of the NTNU model is composed of information from 26 tunnel projects (including some of the high profile Norwegian tunnel projects completed in the 80's) that were compiled by Johannessen [3]. As Bruland [22] has noted, this model includes only a small number of tunnels with extensive rock support requirements.

Table 4. NTNU model for prediction of TBM utilization [2, 3, 21].

Equations	Definition of terms
$U(\%) = \dfrac{T_b}{T_b + T_t + T_k + T_{tbm} + T_{bu} + T_a} \times 100$ $T_b = \dfrac{1000}{I}$ $T_t = \dfrac{1000 \times t_{tak}}{60 \times L_s}$ $T_k = \dfrac{1000 \cdot t_k}{L_h \cdot I}$ $T_{tbm} = 150$	T_b= Time of boring (h/km); T_t = Regrip time (h/km); T_k = Cutter change and inspection (h/km); T_{tbm}= Maintenance and servicing TBM (h/km); T_{bu} = Maintenance and servicing back-up (40 h/km for single track, 90 h/km for double track, 55 h/km for trackless transportation); T_a = Miscellaneous (time for activities such as cleaning, muck car delay, normal rock supporting, surveying, utility in h/km, 185 h/km for single track transportation, 95 h/km for other types); I = Machine net advance rate (m/h); L_s = Stroke length (m); t_{tak} = Time per regrip (5.5 or 4.5) t_k = Time used per changed cutter including time for inspection (for cutter diameters ≤ 432 mm is 0.75 h, and for cutter diameters > 432 mm is 0.833 h); L_h = Cutter life in hour;

***Note: 1. t_k is obtained from cutterheads with front loaded cutters changed under favorable working conditions.**
2. The proposed values for different time items are for "well-organized" tunneling conditions, and long failures are not included [22]. Therefore, extra times should be considered for unfavorable ground conditions as well as long delays for major TBM and BU component failures.

In the calculations and graphs generated for comparison of the reported and predicted values, the following approaches were used:

- Reported T_{tbm} is considered as TBM + Maintenance
- Reported T_a is considered as all downtime items except Regrip, TBM, Maintenance, Cutter, and BU.
- Cutter life, L_h, is calculated based on the number of changed cutters and total boring time.

The predicted and reported downtime values are plotted in Figure 7. Unlike the CSM model, the NTNU model has a wider spread from underestimation to overestimation, and it gives better results for some cases, especially for cutter change, T_k.

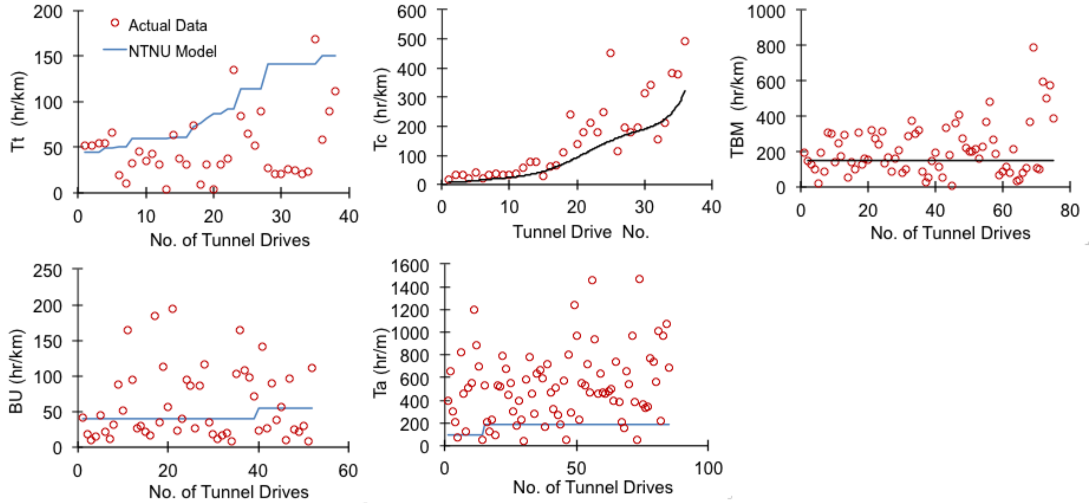

Figure 7. Comparison between reported and proposed values of different activity times using NTNU model.

4.3. Ribacchi and Lembo Fazio's proposed method

As Ribacchi and Lembo Fazio [20] have noted, in general, the total daily working time, T_p, in which a penetration distance of L_p is obtained, can be sub-divided into the following items:

– Penetration time T_p

– Scheduled maintenance time $T_0 = K_0 \times T_d$

– Unscheduled maintenance time, which can be considered proportional to the penetration time (cutter changes, TBM and cutter breakdowns) $T_1 = K_1 \times T_p$

– Service extension and regripping, which are proportional to the penetration length $T_2 = K_2 \times L_p$

In this approach, there are some coefficients (K_0, K_1, K_2) that are considered as fixed values in the mentioned equations. In reality, these coefficients are certainly not fixed. The graphs in Figure 8 are the histograms of distribution of K_0-K_2 in the database used in this work, and show how the three coefficients are scattered for different tunnel projects in different conditions.

There are several reasons for the scatter of these coefficients in different tunnel projects. Some of these reasons are listed as follow:

– The definitions for the mentioned activities and related time are not unique and consistent between different projects. For example, in some projects, the maintenance includes cutter inspection/change, while in the others, these items are categorized separately.

– There are some categories in the model that are omitted or ignored such as transportation delay time.

– The coefficients are not constant values.

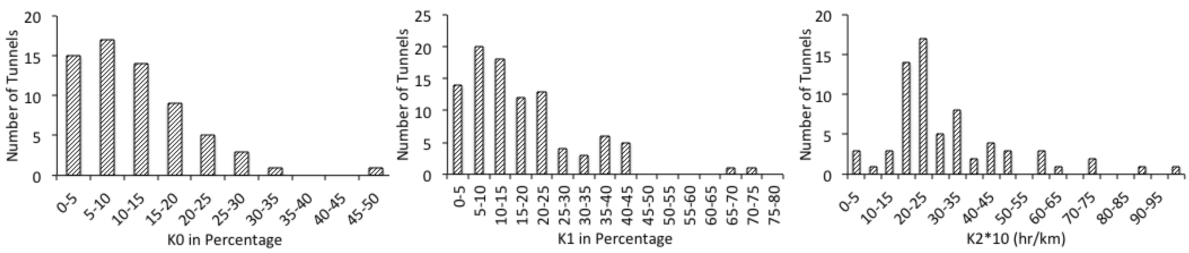

Figure 8. Distributions of coefficient values proposed by Ribacchi and Lembo Fazio [20] in the database.

5. Hard rock TBM downtime model

In this section, the results of the analysis of the data from 89 TBM tunneling projects are presented in terms of the hard rock TBM downtime model. This model includes the results of downtime analysis for each downtime component shown in Table 2 (12 downtime components). In order to obtain reasonable results for each item, the abnormal times and percentage values (cases in which the percentage values of individual activity time were greater than 50%) were excluded from the analysis. The excluded cases are either related to the adverse ground conditions or the incomplete recorded data with high value for "Other" time category.

5.1. Boring time

The common practice in obtaining the boring time is to estimate the penetration rate, and then to convert it to the boring time (Eq. 2). In order to estimate the boring time in h/km, one can use Eq. 2 (see [23, 24] for a comprehensive review on the prediction of penetration rate (PR)).

$$PR = PRev \times RPM$$
$$T_b = \frac{1000}{PR} \tag{2}$$

A new model for hard rock TBMs penetration rate prediction is also offered as follows [24]:

$$FPI = \mathrm{Exp}(1.97 + 0.0063 \cdot \mathrm{RQD} + 0.103 \cdot \mathrm{CAI} + 0.00685 \cdot \mathrm{UCS}) \quad R^2 = 85\%$$
$$PR = \frac{0.06\ RPM \cdot Fn}{FPI} \tag{3}$$

where RQD is the rock quality designation, CAI is the Cerchar Abrasivity Index, UCS is the uniaxial compressive strength in MPa, RPM is revolution per minute, and Fn is disc cutter normal force in kN.

5.2. Regrip time

On the basis of the information in the database, the regrip time is commonly between 20 to 80 h/km for both the open and double shield TBMs. The regrip time can be obtained from Eq. 4.

$$T_r = \frac{1000 \times t_r}{60 \times L_s} + \frac{409000}{R^2} \tag{4}$$

where L_s is the stroke length (m), t_r is the regripping time (min) per stroke, which is between 2 to 6 min, and R is the radius of curvature of the horizontal curves (m).

5.3. Cutter change time

The cutter change/inspection time is highly related to the penetration rate, rock strength and abrasiveness, and geological setting. Figure 9 shows the results of data analysis for cutter change time for rocks with different quartz contents.

5.4. TBM repair time

Figure 10 contains the graphs that show the two most important parameters affecting the TBM downtime including UCS and penetration rate (PR). It should be noted that a lower penetration in the rock with the given strength is usually representative of the larger tunnel diameters and lower TBM cutterhead RPM.

5.5. Back-Up repair time

Figure 11 shows the results of the analysis for BU-related delays for two different tunnel haulage or mucking systems.

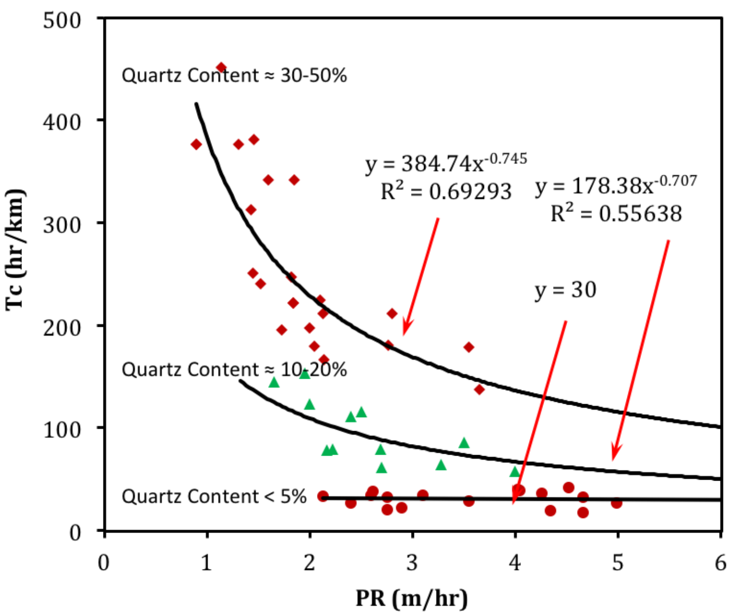

Figure 9. Cutter downtime, Tc.

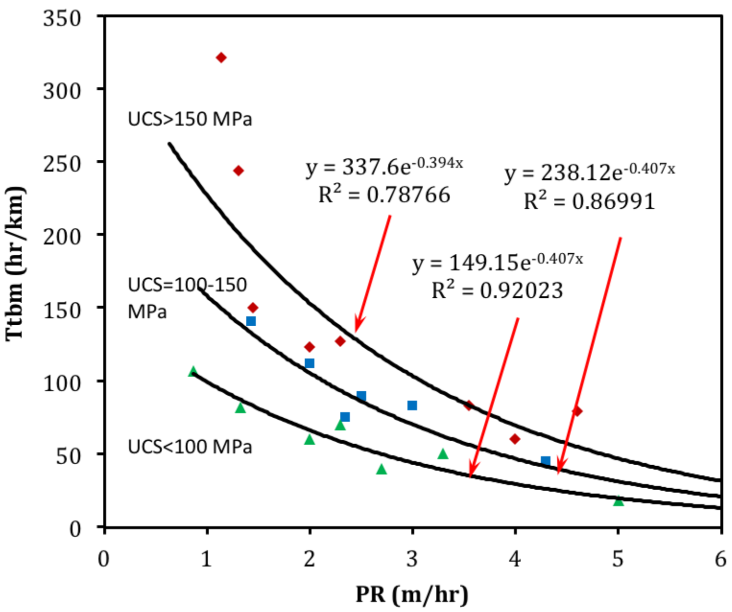

Figure 10. TBM downtime, Ttbm.

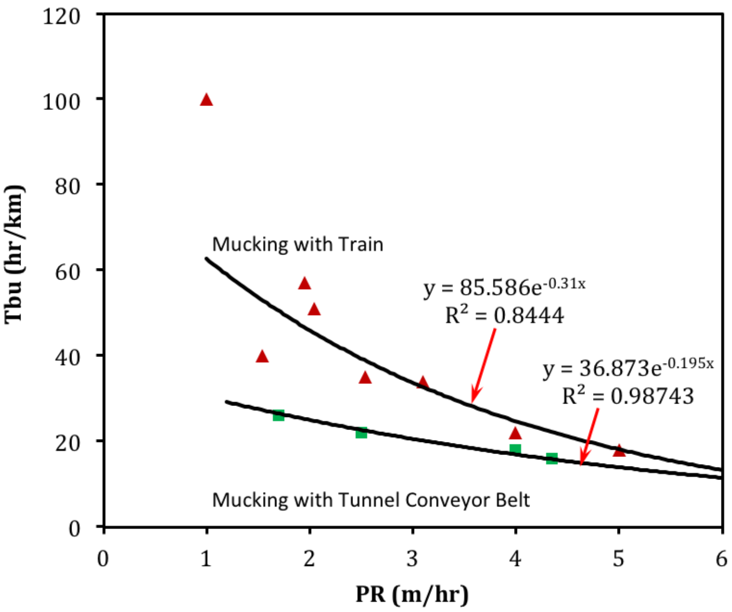

Figure 11. Back-up downtime, Tbu.

5.6. Maintenance

One important issue about maintenance in practice is that it cannot be completely separated from other parallel activities such as utility extension, surveying, and probe drilling. Maintenance-related delays or downtime commonly range from 50 to 300 h/km. Table 5 gives some guidelines for the maintenance time in different conditions on the basis of the information of the database. It should be noted that the current level of the available information is not sufficient to link the guidelines of this table and the TBM condition.

Table 5. General maintenance downtime in different conditions.

Condition	Tm (h/km)	Comment
Good	50-100	Massive soft to medium rock
Normal	100-200	Massive hard rock
Poor	300	TBM prone to high clogging and high water inflow in poor cementations, presence of expansive clay, very high rock strength for TBM

5.7. Surveying downtime

Surveying downtime ranges from 0 to 25 h/km (close to 0 for most of the cases). In tunnel curves, as the CSM model proposed, an additional time of $192000/R^2$ (R is the radius of curvature of horizontal curve in m) is required.

5.8. Utility installation downtime

Utility extension downtime ranges from 10 to 100 h/km with an average of 40 h/km. As proposed by the CSM model, an additional time of $1.3\times\theta$ for different tunnel slopes (θ is tunnel slope in degree) is required.

5.9. Transport-related downtime

Table 6 shows the approximate muck transport downtime for different conditions. Obviously, in long tunnels, this delay item might increase a lot due to high frequency of equipment breakdowns. This issue is reflected approximately in poor and very poor transportation conditions.

Table 6. Muck transport downtime in different conditions.

Condition	T_{tr} (h/km)	Comment
Very Good	<50	Tunnel conveyor belt prone to no or very low breakdowns
Good	50	Tunnel conveyor belt/Train prone to low breakdowns
Normal	150	Tunnel conveyor belt/Train prone to normal breakdowns
Poor	350	Tunnel conveyor belt/Train prone to high breakdowns (especially in long tunnels)
Very Poor	>500	Tunnel conveyor belt/Train prone to very high breakdowns (e.g. simultaneous breakdowns for locos, wagons, and switches)

5.10. Ground support installation downtime

In the case of shielded TBMs, the downtime for support is typically fixed for a tunnel project. In the case of open TBM, as the RMR value decreases, the demand for ground support installation increases. Figure 12 shows the approximate support installation time for different scenarios. The sharp downturn on the ground support installation downtime in low RMR values for shielded machines reflects the potential needs for ground improvements in weak rock masses to avoid face collapse and ground squeezing issues (see [25-29]).

5.11. Groundwater condition related downtime

Water inflow might interrupt the excavation process for different reasons. Some examples are the difficulties due to wet muck conveying, pumping, and tunnel face instability. Figure 13 shows an approximation for downtimes related to water inflow.

5.12. Other downtimes

Consider 0 to 200 h/km for the case of experienced to unexperienced crew. For the case of very experienced crew, lower the total downtime by 200 h/km.

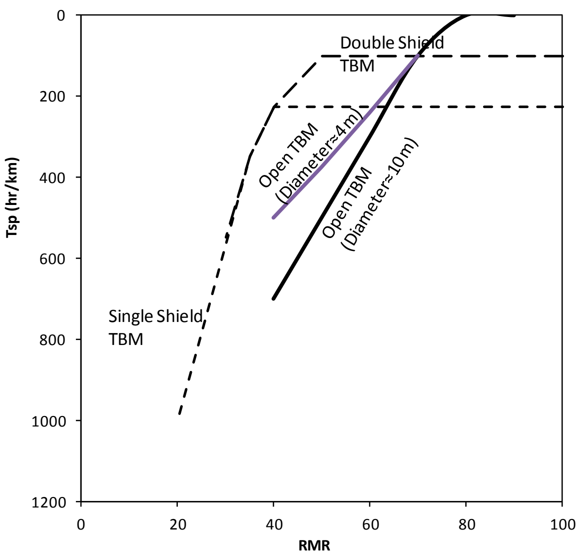

Figure 12. Supporting downtime, Tsp.

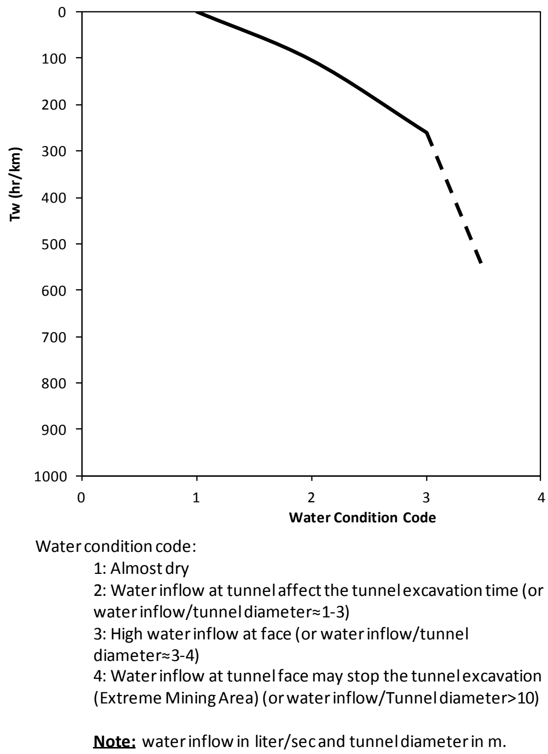

Figure 13. Downtime related to water inflow, Tw.

6. Example

Figure 14 shows an example of using the proposed model for the utilization and advance rate prediction for an open TBM with a diameter of 3.9 m. The rock consists of argillite with a low quartz content and a UCS of 50 MPa. The expected penetration rate is 4.7 m/h. This TBM uses 17" cutters. The haulage system is rail-bound. The stroke length is 1.25 m. Table 7 shows a summary of the estimated downtimes and the utilization rate (21%). After calculating the utilization, the daily advance rate is predicted from the multiplication of the utilization and penetration rate (23.5 m/day).

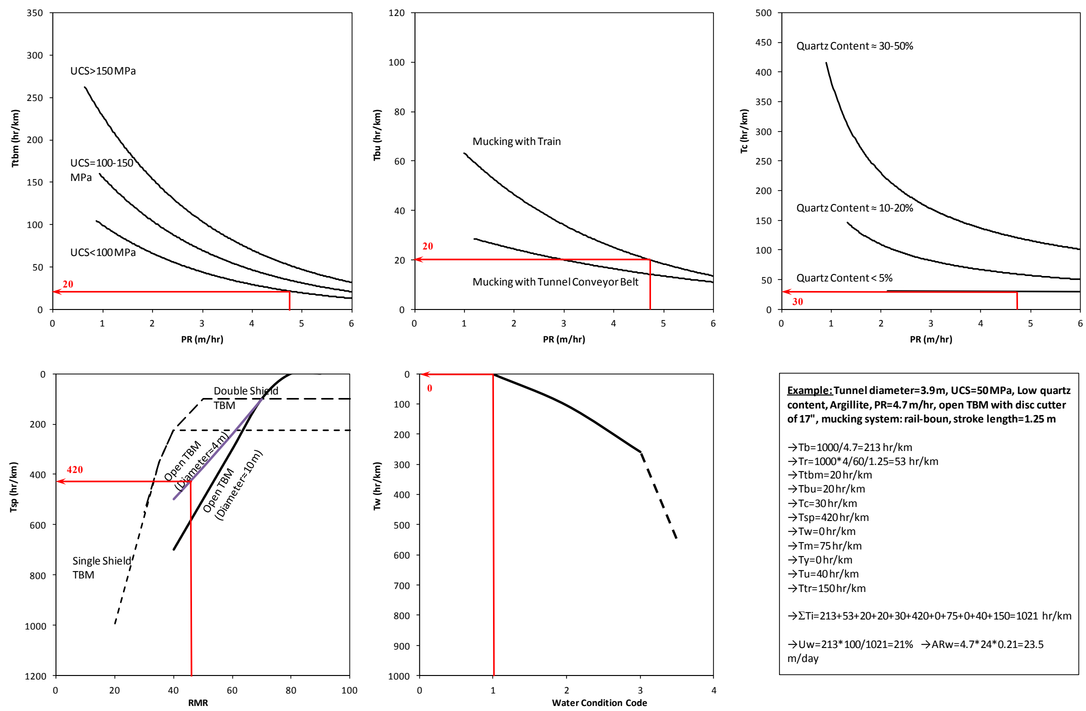

Figure 14. Example of using new model graphs and formulas.

Table 7. Summary of downtime values.

Item	Value (h/km)
Tb	213
Tr	53
Ttbm	20
Tbu	20
Tc	30
Tsp	420
Tw	0
Tm	75
Ty	0
Tu	40
Ttr	150
Sum	1021
Uw (%)	21
ARw (m/day)	23.5

7. Comparative study of new model

Table 8 and Figure 15 show the results of the Uw and ARw predictions for 12 recently completed tunnel projects using the guidelines and methodology shown in Figure 2. As it can be seen, the results are close to the actual values with high coefficient of correlations and low root mean square errors. This confirms the model works well for the recent tunnel projects. The results of this work can help to improve the process of the utilization factor evaluation, which is one major component of every tunneling project' cost and time evaluation. Further improvements of the new model are still under study when more data from various tunneling conditions is added to the database. The advanced methodology of tunnel activity simulation may also improve the utilization factor evaluation further [15] but it certainly requires several detailed data from the activity time distribution. Currently, the level of the available information is not sufficient to link the guidelines of this paper and the simulation modeling but this will also be further studied in the future to enhance the predictive capabilities of the new model.

Table 8. Comparative study for Uw and ARw prediction for 12 tunnels.

Tunnel Name	Rock Type	Diameter (m)	UCS (MPa)	TBM Type	RMR	Fn (kN)	RQD	PR (m/hr)*	Uw (%)*	ARw (m/day)*
Ghomroud	Sandstone	4.5	53	DS	49	125	60	4.3 (4.4)	29 (26)	30 (28)
Zagros	Limestone	6.73	50	DS	44	150	60	2.7 (3.0)	30 (35)	20 (25)
Pieve	Granodiorite	4.05	195	DS	80	220	100	1.5 (1.7)	45 (40)	17 (16)
Milyang	Granite	2.6	246	Open	84	143	93	0.9 (0.9)	45 (48)	10 (10)
Manapouri	Granite	10.05	200	Open	61	267	97	1.1 (0.9)	40 (46)	10 (10)
New York tunnel	Gneiss	3.84	62	Open	70	197	80	4.0 (4.3)	32 (27)	32 (28)
Frasnadello-Main	Argillite	11.8	30	SS	33	100	55	1.7 (1.7)	30 (35)	12 (15)
Frasnadello-Pilot	Argillite	3.9	60	Open	45	150	60	4.7 (5.1)	22 (19)	25 (24)
Rapid transit subway	Chalk	6.55	10	Open	60	200	90	~5 (5.2)	- (34)	40-60 (42)
River Mt.	Conglomerate	4.3	32	Open	60	180	60	9.3 (9.4)	25 (24)	55 (55)
Govalle Segment B	Chalk	3.2	5	SS	60	180	60	10.6 (11.9)	18 (15)	45 (44)
Syar	Sedimentary	3.6	50	Open	60	200	60	6.4 (8.5)	30 (21)	47 (42)

***(26) refers to the predicted value.**

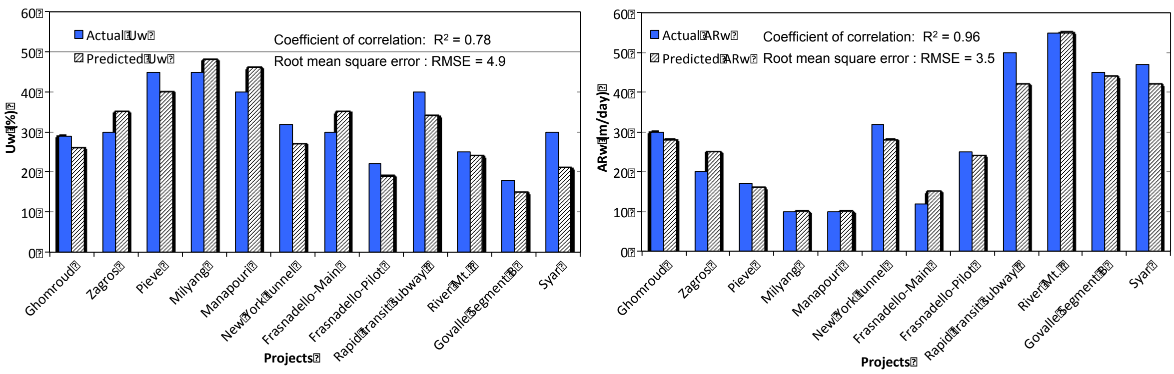

Figure 15. Results of comparative study for predicted Uw and ARw.

8. Conclusions

In this paper, comparisons between the predicted and actual TBM downtimes indicate that for many of the studied cases, the existing predictive models do not generate accurate estimates. For a majority of the cases, the predicted values are lower than the reported ones, and in some cases, the difference is several times the predicted values. This means that in most cases, the models underestimate the downtimes of the TBM or overestimate the utilization rate.

Part of the problem is the complexity of the jobsite activities and their overlap and parallel or linear relationships as well as the influence of various non-technical or site management issues on TBM operation that is not directly reflected in various models and their predictions. Furthermore, the existing TBM utilization models were developed a couple of decades ago, and they require new updates in their models to match the new technological advancements and to reflect the exact effect of variation of the machine types, ground conditions, contractor experiences, and site-related requirements. In order to achieve more accurate estimates for the downtimes and overall TBM utilization, an in-depth analysis of various downtime components was conducted on the basis of a database of 89 TBM tunneling projects with a focus on the most commonly used rock engineering properties such as compressive strength and ground water inflow. Using 12 most frequent downtime categories identified from the contractors' reports, a new hard rock TBM downtime model was generated with a set of graphs, formulas, and tables. The results obtained show that the coefficient of correlation for the downtime components' formulas range between 0.56 and 0.99. The evaluation of the predicted results of the new model for some recently completed tunnels show that there is a good agreement between the predictions and actual values for both utilization and advance rate with high coefficients of correlation (0.78 and 0.96 for Uw and ARw, respectively). A further study with more detailed data and also simulation techniques is currently underway, and will be discussed in the follow-up publications. One note about the new introduced model is that it does not attempt to evaluate TBM operation under extreme conditions associated with phenomena such as extreme water inflow, gassy ground, and very soft ground. In order to address these conditions, more data is required. One may accept that estimating machine performance in such cases is nearly impossible since the impacts and extent of these incidents and mitigation measures are commonly unpredictable.

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معرفی مدل تحلیل تأخیرهای ماشین‌های TBM سنگ‌های سخت بر اساس اطلاعات پروژه‌های تونلی

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چکیده:

مطالعه و بررسی تأخیرهای ماشین‌های تونل‌زنی در یک پروژه تونلی به لحاظ ارتباط مستقیم آن‌ها با برآورد ضریب بهره‌وری و نرخ پیشروی از اهمیت بالایی برخوردار است. در این پژوهش، با استفاده از اطلاعات تأخیرهای فعالیت‌های مختلف تعدادی از تونل‌های حفاری شده با TBM در سنگ سخت، به اعتبار سنجی مدل‌های موجود در زمینه برآورد ضریب بهره‌وری پرداخته شده است. نتایج این مطالعات نشان می‌دهد که این مدل‌ها عمدتاً تخمین‌های ضعیفی به دست می‌دهند که عمدتاً به واسطه قدیمی بودن بانک اطلاعاتی آن‌ها است. به منظور توسعه یک مدل تأخیرهای مناسب با درصد خطای تخمین کمتر، تأخیرهای طبقه‌بندی شده در بانک اطلاعاتی جمع‌آوری شده از پروژه‌های تونلی مختلف دنیا مورد تحلیل آماری قرار گرفت و نتایج آن در قالب تعدادی فرمول، جدول و نمودار تحت عنوان «مدل تحلیل تأخیرهای ماشین‌های TBM سنگ‌های سخت» ارائه شده است. اعتبار سنجی مدل ارائه‌شده به وسیله اطلاعات ۱۲ تونل، نشان می‌دهد که توافق مناسبی بین نتایج مدل توسعه داده‌شده و مقادیر واقعی ضریب بهره‌وری و نرخ پیشروی وجود دارد. نتایج این مطالعه می‌تواند کمک مؤثری در برآورد زمان و هزینه تکمیل یک پروژه‌های تونلی داشته باشد.

کلمات کلیدی: تونل، TBM، نرخ پیشروی، ضریب بهره‌وری، تأخیر.
