Geopersia 2023 13 (1): 1-14
DOI: 10.22059/GEOPE.2022.304879.648636

RESEARCH PAPER

Assessment of Double Shield TBM performance by using downtime index (DTI)

Majid Tajik, Mashalah Khamehchiyan *

Department of Engineering Geology, Tarbiat Modares University, Tehran, Iran

Received: 14 October 2021, Revised: 12 July 2022, Accepted: 03 October 2022

Abstract
In mechanized tunneling, TBM performance prediction is vital to estimate the time and cost of the project. Therefore, calculating the performance parameters is so important. The utilization coefficient depends on management parameters, personal ability, logistic utility and equipment, tunnel characteristics, objectives and geological conditions. Although in each of the main models same as CSM, NTNU and Q_{TBM}, the specific parameters used to estimate the utilization coefficient, the effect of management factor and interactions and overlapping factors not considered. On the other hand, many parameters have a severe dependence on each other and may simultaneously affect the performance of the TBM. Therefore, the interaction matrix can be used to evaluate the interaction of parameters on each other and on TBM performance. The effect of 18 parameters on the utilization coefficient was evaluated by the matrix method in Karaj water conveyance tunnel. The interactions of these parameters show that the lack of utility services and shift change have the most significant impact on TBM performance. By recording the actual delays in each parts of tunnel, the downtime index (DTI) is obtained; this index has a direct relationship with tunnel boring time and is inversely related to TBM performance.

Keywords: TBM Performance, Interaction Matrices, Utilization Coefficient, Downtime Index, Karaj.

Introduction

Tunnel boring machines (TBMs) have been extensively used for tunnel construction in rock and soil (Mahmoodzadeh et al., 2020; Xu et al., 2021). The accurate prediction of TBM performance is crucial for estimating project schedules and selecting machine types and specifications (Gong and Zhao, 2009; Goodarzi et al., 2021). The TBM performance is directly related to the ground condition. This performance includes valuable information such as rpm, penetration rate, thrust, and torque that make the possible estimation of some important tunnelling parameters such as field penetration index (FPI) (Hashemnejad et al., 2020). Many theoretical, empirical and semi-empirical formulations have been proposed to predict TBM performance (e.g., Ramezanzadeh, 2005; Yagiz, 2008). These formulations have been developed using linear and non-linear regression analysis of the studied performance and influential factors. However, the datasets tend to be collected from a given project; Thus, the application scope of the empirical formulations is typically limited to a specific project (Xiao et al., 2022). To overcome this problem in recent years, to improve the performance models and provide useful precautions against possible geological hazards, the use of big data and machine learning methods has attracted significant research interest. Large volumes of artificial intelligence (AI) research outcomes have emerged, e.g., the integration of machine learning with numerical modelling methods such as finite element method and digital modelling

---

* Corresponding author e-mail: khamechm@modares.ac.ir

methods such as building information modeling for achieving the real-time modelling tunneling process (Ninic et al., 2017; Freitag et al., 2018; Alsahly et al., 2020; Nincic et al., 2020). The studies conducted by Salimi et al. (2016), Fattahi et al. (2017) and Armaghani et al. (2018) are among the leading studies in this field.

The main objective of the current study is to examine boreability characteristics of rocks in Karaj water conveyance tunnel route and developing a new model with higher accuracy to estimate performance of TBMs in these rocks. To reach this goal, the actual data obtained from selected sections of Karaj water conveyance tunnel, were collected, screened, and analyzed.

TBM performance prediction models

Many studies have been done about TBM performance. In some TBM parameters such as rolling forces acting on the V-shaped disc cutter (Roxborough and Phillips, 1975), rolling and normal forces on the disc cutter (Snowdon et al., 1982), essential tensional stress for chipping (Sanio, 1985) shift change, TBM operation time and excavated length (Abd Al-Jalil, 1998) are a priority. Others have used only intact rock properties, for example, uniaxial compressive strength (Tarkoy, 1975; Graham, 1976), Brazilian tensional strength (Farmer and Glossop, 1980) and abrasion resistance of sedimentary rocks (Nelson et al., 1983; Sato & Itakura, 1991). Then, some researchers also added the properties of the rock mass. Rock structure rating (RSR) and uniaxial compression strength (UCS) (Innaurato et al., 1991), rock mass index (RMi) (Palmstrom, 1995) and rock mass excavability (RME) (Bieniawski et al., 2007b), rock mass rating (RMR) and Q system (Sapigni et al., 2002), UCS, Brazilian tensile strength, brittleness/toughness, distance between planes and orientation of discontinuities (Yagiz, 2008), UCS and discontinuities spacing (Hassanpour et al., 2009) are examples of these studies.

Others used the numerical methods to estimate the TBM performance (Gong and Zhao, 2009), gene expression programming as an extension to genetic algorithm and genetic programming (Zare Naghadehia et al., 2018) and Discrete event simulation (Frough et al., 2019).

Gong et al. (2006) studied the effect of orientation and spacing of joints on rock brittleness by using numerical models. Kim (2004) modeled the influence of RMR, RQD and water on the performance index by using the fuzzy logic method. Frough et al. (2012) also examined the effect of rock mass rating (RMR) on utilization coefficient and TBM performance. Farrokh (2012) used some rock parameters for penetration rate estimate. Moosazadeh et al. (2018) simulated TBM utilization in Tabriz urban railway. Benardos and Kaliampakos (2004) estimated the effect of RMR, UCS, RQD, safety factor, underground water condition and tunnel depth at a TBM advance rate by using the neural network method. In these models, researchers focus on geological conditions and pay less attention to the impact of other delays on TBM performance.

Colorado School of Mines (CSM), Norwegian University of Science and Technology (NTNU) and Q_{TBM} are known as the principle models of TBM performance prediction. These models have a different basis. Usually, on a project, two methods are used together. CSM is a theoretical-experimental model, which Ozdemir presented the first review in 1977 (Rostami and Ozdemir, 1993). This model is based on data gathered from large-scale linear cutting test, which can estimate the required forces for cutting the rock and related parameters. In CSM model, the effect of discontinuities on the TBM penetration rate is not considered (Ramezanzadeh et al., 2002; Rostami et al., 1997).

NTNU model after the start of the mechanized tunneling has been developed in Norway and has been updated with new data. This model is based on systematic data that developed from 35 projects and more than 250 kilometers of tunnels (Bruland, 1998).

Q_{TBM} model was established on Q-system and Barton (1999) suggested this model to estimate TBM penetration and advance rate. The effect of discontinuity orientation, compressive and tensional strength of intact rock, cutter life index (CLI), quartz content, rock and machine interaction parameters were considered (Barton, 1999). Q model predicts advance rate by case recorded data from 145 TBM tunnel and totaling more than 1000 Km excavation (Barton, 2000).

In CSM, NTNU and Q_{TBM} models, there are different methods for estimating the utilization coefficient. In each model, maybe some parameters considered that are not important in other models. In Table 1, the factors affecting the utilization coefficient in CSM, NTNU and Q_{TBM} models are compared.

Rock Engineering Systems (RES) application

Although in TBM performance prediction models, the affecting parameters and the importance of these parameters and their impact on the utilization rate has been determined. Nevertheless, many parameters have severe dependence with each other and may effect on TBM performance simultaneously. Then in order to determine the TBM performance, it is necessary to separate the efficient parameters and determine the influence of each parameter on each other.

Therefore, in this study, each activity and inactivity (downtime) of persons and TBM was selected as affecting parameter on utilization coefficient and then by forming a matrix the effect of the interaction of parameters with each other and TBM performance is evaluated. This method was derived from Rock Engineering Systems (RES) Hudson's approach, which is a systematic method for analysis and classification of rock engineering projects.

In this method, the interaction matrices are the powerful tools that evaluate the interaction effects of the parameters to each other on an equal scale. Usually, these metrics are used to gather the individual coefficients and highlights the interaction between the elements (Hudson & Harrison 1997). In addition, the interaction matrices were used for identifying the critical parameters, effective pathways, recursive loops and evaluation of selected engineering technique (Hudson, 1992). In interaction matrices, effective parameters are on the main diagonal matrix and the interactions between parameters are on the non-diagonal elements (Hudson, 1992).

Table 1. Comparison between the factors affecting the utilization coefficient (Frough et al., 2011)

Category	Parameter	CSM	NTNU	Q_{TBM}
Ground Condition	Discontinuities condition	No	Yes	Yes
	RMR	Only for rock Support	No	No
	Q	No		
	Ground water	Yes	Yes	Yes
	Abrasive stone			
	Disk cutter change			
	Rock fall	No		
	Investigation (Probe, TSP)		No	No
tunnel Characteristics	Curved path	Yes		Yes
	Diameter	No		
	Slope	Yes		
	Rock support			
	Grouting and Sealling	No		
Management and Logistics	Survey	Yes	Yes	No
	support services			
	Transport			
	TBM Maintenance			
	Back up Maintenance			
	Unexpected repairs		No	

Numerous researchers have been using the RES for analyzing rock-engineering plans. Slope failure hazard zoning in Turkey (Ceryan and Ceryan, 2008), ranking of potential instability of natural slopes (Rozos et al., 2008; KhaloKakaie & Zare naghadehi, 2012), rockfall hazard assessment along a major road in China (Zhang et al., 2004), stability analysis of Seymare water conveyance tunnel (Sadeghi & rasouli, 2011), usage of geological and management parameter for TBM performance prediction in each geology zone (Yaghoubi, 2010; Yavari et al., 2011), estimation of required rotational torque to operate horizontal directional drilling in natural gas transmission pipeline projects (Fattahi, 2018), Assessment of the Rock Mass Fragmentation (Azadmehr et al., 2019) and Powder factor prediction in blasting (Adesida, 2022) are examples of the use of RES in rock engineering.

TBM performance and affecting parameters in the Karaj-Tehran water Conveying tunnel was investigated by using the systemic approach.

Case study

Water conveyance tunnel from Amirkabir dam to water treatment No. 6 of Tehran with about 30 km long and 16 m^3/s capacity is a part of the water supplying project in the western part of Tehran. A double shield TBM with 4.66 m diameter excavated this tunnel and the final diameter is 3.9 meters. Precast concrete segments (5+ key) with a 25 cm cover the final lining. The location of the tunnel is shown in Figure 1.

The first part of this tunnel is located between refinery No. 6 and near the village of Kondor (ET-K" section) which is 16042 meters long. The second part of the water conveyance tunnel (K"-BR section) with a 13440-meter length is excavated by same TBM. In this study, the daily boring reports, geological maps and data collected during the construction of the project is used.

Geology of the tunnel

This tunnel is located in the south domain of central Alborz. The central Alborz is a stratigraphic state with complex structure and unique features that it is located in the southern part of Karaj-Soloughan area (Sahel consultant engineers institute, 2009).

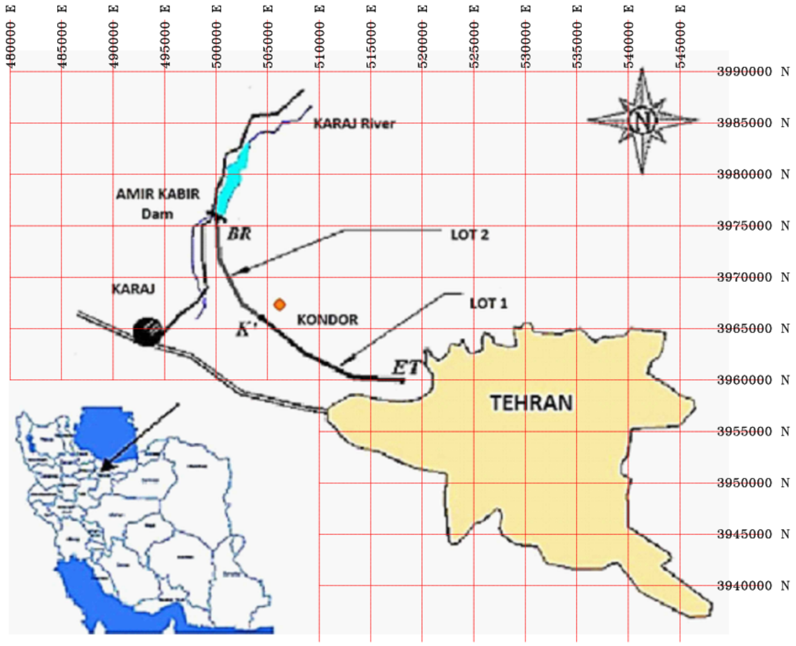


Figure 1. The geographical location of Karaj-Tehran water conveyance tunnel (Frough, et al., 2012)

This area belongs to tertiary zone and includes several sedimentary complexes of late middle Eocene Karaj Formation (Gansser & Huber, 1962).

Along the tunnel path, Karaj formation section is divided into middle Tuff, Asara shale, upper Tuff and Kandovan shale that each section has distinct rock units. Tuff, sandstone, siltstone, lava and Agglomerate are lithology of rock units that can be seen in folded sedimentary layers' form (Sahel consultant engineers institute, 2011). Usually, intrusive rocks in the form of dikes are found in sedimentary units (Figure 2).

Due to the fine texture and filling joints, most rock units in the tunnel have poor permeability then the hydrogeological value is very low for Aquifers (Sahel consultant engineers institute, 2009).

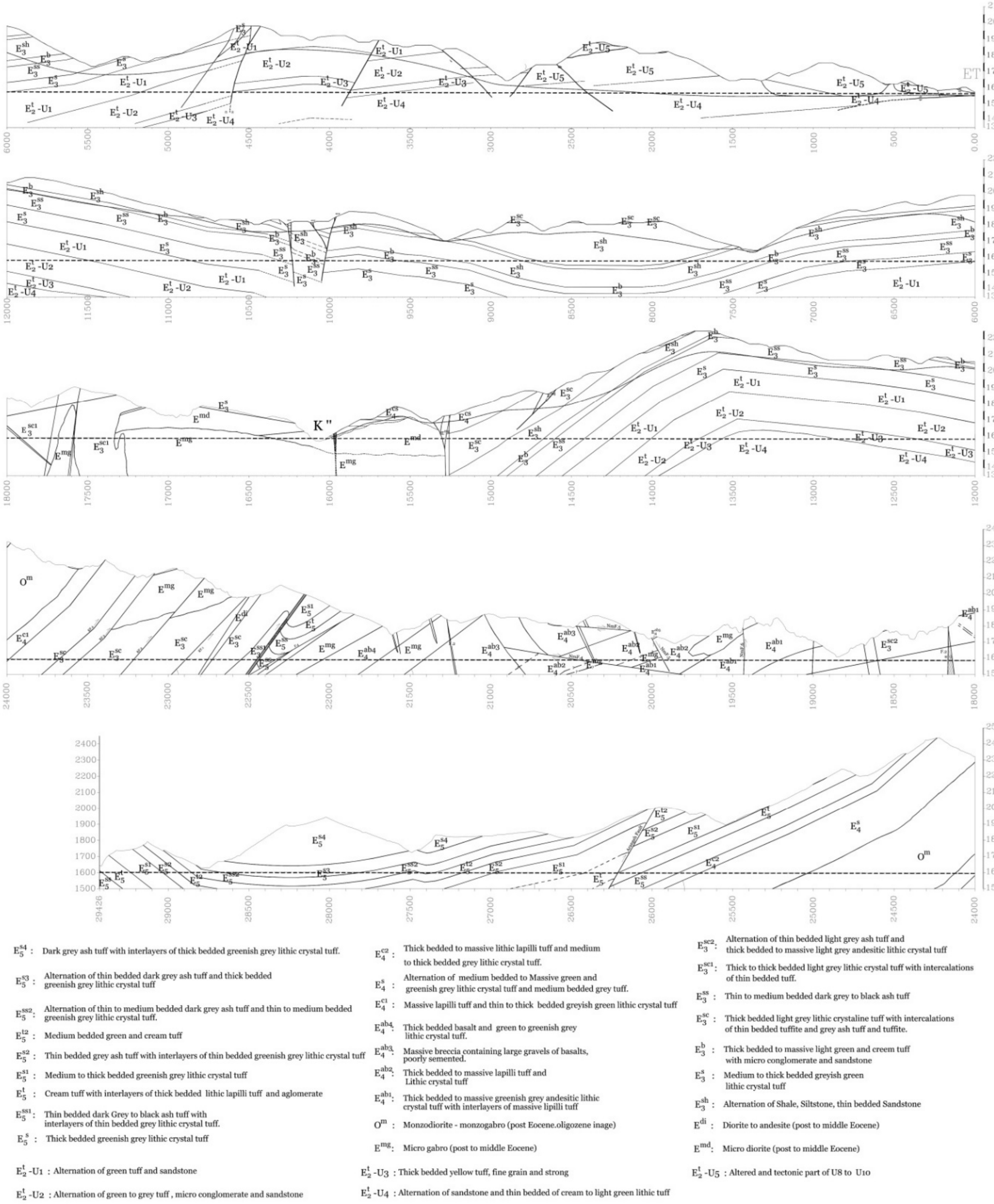


Figure 2. Geological Profile of Karaj Tunnel (LOT I, II) (Sahel consultant engineers institute, 2011)

Delay investigation in the interaction matrix

In order to predict the TBM performance, study of all the affecting parameters on penetration rate and utilization coefficient is necessary. In a systemic approach, detecting the affecting parameters on TBM performance is so important, adding to the effect of each parameter on machine performance, the state of relations between parameters in the matrix is also necessary. Depend on the geological conditions of the tunnel path (rock properties, gas, underground water, overburden), type of TBM (Diameter, open, single or double shield), equipment supply, tunnel geometry, aim of the project (water conveyor, road tunnel), these parameters usually differ. In this project, except these parameters, location of the project and access ways to tunnel affects the machine performance.

In this project according to schedule, machine and personnel activities are programmed for three shifts in a day and 7 days per week. In each work shift, all factors that may influence on delay or stop of the machine are listed individually in minutes. Then in order to facilitate research, 18 affecting parameters on utilization coefficient were selected. These parameters can be representative of a group of activities or delays (Table 2).

In the matrix method, each parameter is assigned a score. The ranking parameters can better manage projects in order to increase utilization coefficient and then TBM performance. Ranking the matrix element has been done with regard to the impact of a parameter on each other. During the project, the more the interaction of each parameter, the higher rank may have. Finally, according to table 3 the coding matrix interaction has introduced five classes 0 to 4.

Table 2. The parameters affecting the utilization coefficient in mechanized tunneling

NO.	Parameter	Description
P1	Boring	Boring
P2	Gripping / Move	TBM / Backup Move
P3	Ring Building	Segment Installation
P4	Routin Maintenance	Checking tanks, sensors, gauges, grease pump; lubrication, rotary part control and …
P5	Cutter Check	Cutter disc check; cleaning and welding of cutter head
P6	Cutter change	Replacing the worn/ damage cutter disc and installing a new one
P7	VMT & Survey	Survey Station Installation; TBM Steering System Problems (VMT)
P8	Utility Service (water, air and power)	Electricity power outage and cabling, air compressor, dewatering pump/pipe and ventilation problems
P9	Lack of materials	Delayed supply of hydro-mechanical and electrical components; disc cutter, concrete segment, bolt and …
P10	Mechanical & Hydromechanical problems	Mechanical & Hydromechanical problems such as Conveyor belt, Cylinders, Wheels, Segment erector and ...
P11	Electrical problems	Electrical problems such as PLC, electromotors, electrical panels, transformers
P12	Transportation & Conveyor problems	Loading difficulties, delay in train arrival, derailment, Wagon tippler problem in portal, Conveyor belt problems
P13	Shift change	Delay or absence of staff in the tunnel
P14	Ground improvement (Probe Drilling and Grouting)	Probe Drilling, Pre-Grouting, Post grouting, face support,
P15	Washing & Cleaning	Washing of segment feeder and tail shield, backup cleaning
P16	Train exchange & unloading problems	Rail track installation, car mover Problem; unloading in the backup (Segment, Pipe, Parts)
P17	Geological Problems	Downtime due to tunnel water leakage, cutter head and brackets clogging, quartz-bearing rocks, rockfall
P18	Lunch, safety meeting & Others	Lunchtime, HSE visit, employer inspection and …

In order to percept, the interaction of parameters and the effect on the boring machine 17 parameters along with parameter of boring time P1 are placed on the diagonal of the matrix. In fact, P1 is representative of the utilization coefficient that investigated as a parameter for determining TBM performance (Figure 3).

With regard to the construction of the matrix is clear that each row passing through elements shows the effect of that element on other parameters. Vice versa, each column represents the other parameter influence on this element in the system. Thus, the interaction of the P1 column shows how activities and delays the effect on boring time. Similarly, the row, which passed through this element, indicates effect of boring time on other parameters. This explains that all parameters (2 to 18) in this matrix have a negative effect on P1. Therefore, increasing the time of each parameter leads to reduce boring time and thus reduce the TBM performance.

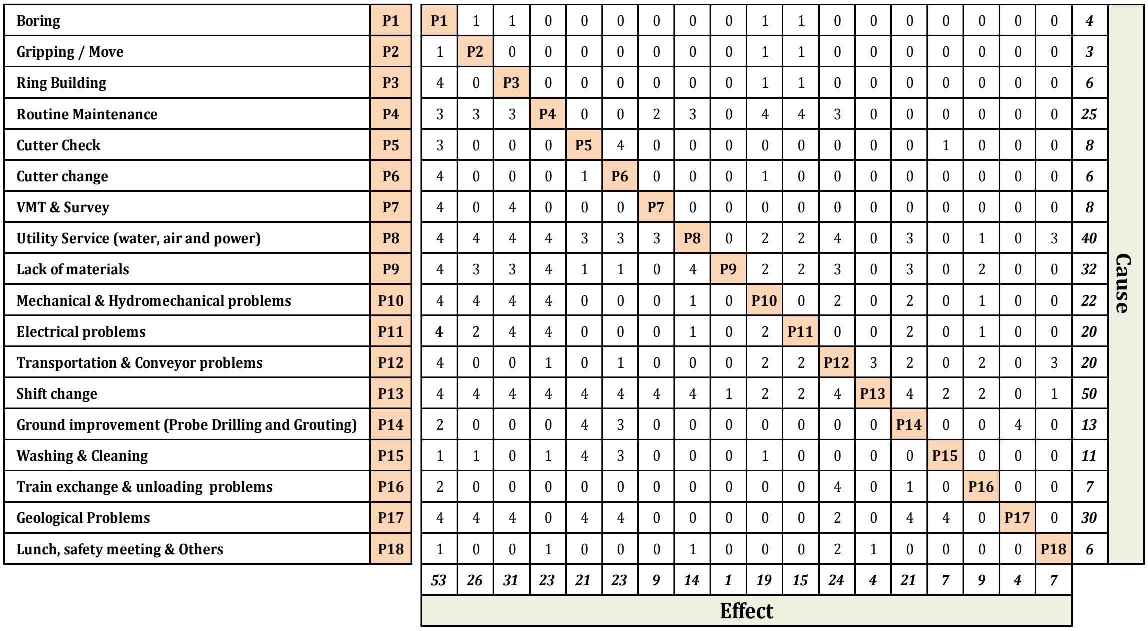
The expert semi-quantitative (ESQ) method based on an encoding matrix and a questionnaire survey of experts is used. This method is more applicable than other matrix coding methods.

The sum of each row and column of the coding matrix is calculated and is presented in order to cause and effect. Therefore, C represents the effect of a parameter on the system and E indicates the influence of the system on this parameter (KhaloKakaie & Zare naghadehi, 2009).

For each parameter, the sum of all codes in each row as a Cause "C" and each column as effect "E" is calculated. Then, Cause and effect diagram is used on values and the difference between low and high interaction is shown (Figure 4).

Table 3. describing the conventional ranking in the interaction matrix

code	interaction description
0	The parameter never affects the other parameter.
1	The parameter has very little effect on the other parameter.
2	The parameter has little effect on the other parameter.
3	The parameter greatly affects the other parameter.
4	The parameter strongly influences the other parameter.



																				Cause
Boring	P1	P1	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	4
Gripping / Move	P2	1	P2	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	3
Ring Building	P3	4	0	P3	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	6
Routine Maintenance	P4	3	3	3	P4	0	0	2	3	0	4	4	3	0	0	0	0	0	0	25
Cutter Check	P5	3	0	0	0	P5	4	0	0	0	0	0	0	0	0	1	0	0	0	8
Cutter change	P6	4	0	0	0	1	P6	0	0	0	1	0	0	0	0	0	0	0	0	6
VMT & Survey	P7	4	0	4	0	0	0	P7	0	0	0	0	0	0	0	0	0	0	0	8
Utility Service (water, air and power)	P8	4	4	4	4	3	3	3	P8	0	2	2	4	0	3	0	1	0	3	40
Lack of materials	P9	4	3	3	4	1	1	0	4	P9	2	2	3	0	3	0	2	0	0	32
Mechanical & Hydromechanical problems	P10	4	4	4	4	0	0	0	1	0	P10	0	2	0	2	0	1	0	0	22
Electrical problems	P11	4	2	4	4	0	0	0	1	0	2	P11	0	0	2	0	1	0	0	20
Transportation & Conveyor problems	P12	4	0	0	1	0	1	0	0	0	2	2	P12	3	2	0	2	0	3	20
Shift change	P13	4	4	4	4	4	4	4	4	1	2	2	4	P13	4	2	2	0	1	50
Ground improvement (Probe Drilling and Grouting)	P14	2	0	0	0	4	3	0	0	0	0	0	0	0	P14	0	0	4	0	13
Washing & Cleaning	P15	1	1	0	1	4	3	0	0	0	1	0	0	0	0	P15	0	0	0	11
Train exchange & unloading problems	P16	2	0	0	0	0	0	0	0	0	0	0	4	0	1	0	P16	0	0	7
Geological Problems	P17	4	4	4	0	4	4	0	0	0	0	0	2	0	4	4	0	P17	0	30
Lunch, safety meeting & Others	P18	1	0	0	1	0	0	0	1	0	0	0	2	1	0	0	0	0	P18	6
Effect		53	26	31	23	21	23	9	14	1	19	15	24	4	21	7	9	4	7	

Figure 3. coding the interaction matrix composed of 18 affecting parameters on TBM performance (Karaj tunnel)

As shown in Figure 4, the diameter of the Cause-Effect diagram is the locus C=E that the value of C+E is increasing along the diagonal. The points at the bottom right of the graph have C-E higher value and indicate parameters that have mastered the system. Conversely, parameters that affect the system are placed in the upper left of the graph and have lower values of E.

The Cause-Effect diagram can indicate the positive and negative interaction effects of each parameter on the TBM performance. For example, fig. 4 shows that the boring parameter (P1), move/gripping (P2) and Ring building (P3) are quite impressed with the system so they have little impact on other activities and delay the TBM. Instead, shift change (P13), utility services (P8), lack of materials (P9) and geological problems (P17) have the highest control over their systems. Therefore, they can lead to significant changes in other activities.

The intensity of interaction histogram can be achieved by the sum of cause and effect (C+E) for each parameter (Figure 5).

The selection of C+E as a factor of differentiation between parameters is because of the concentration on the role of system interaction. Generally, if the interaction of a system is high, the expectation of good performance cannot be achieved. Because a little change in a parameter has a good chance to affect the system condition significantly. Then the probability of performance decline is higher.

The fig. 5 shows the parameters 1,4,8 and 13 that are boring, routine maintenance, utility services and shift change have the most influence on a system and then a little change in these parameters greatly affects the utilization coefficient. It has proven that a delays of staff or electricity and water supply for a boring machine leads to stop all activities. Then in order to improve the performance, good management of P8 and P13 is of utmost importance.

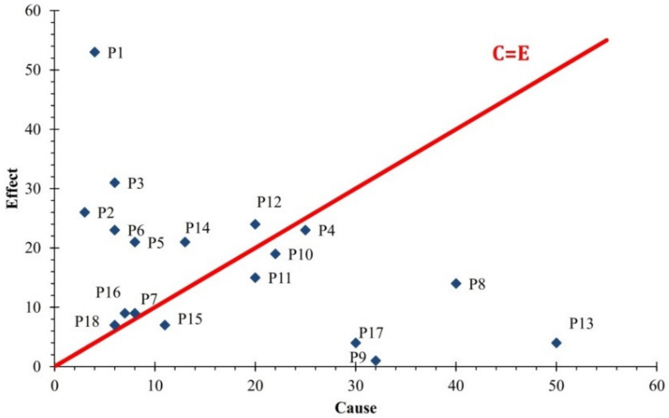


Figure 4. Effect (E) and cause (C) value for selected parameters

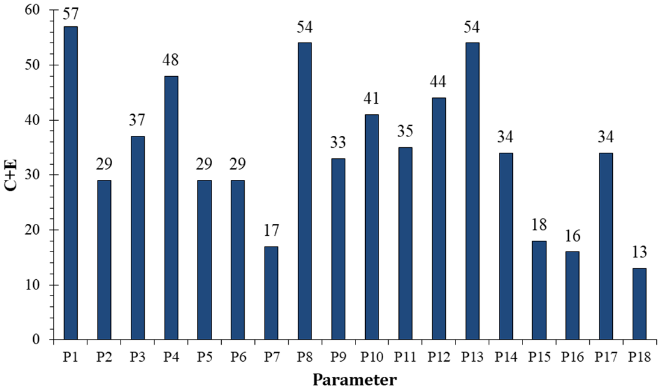


Figure 5. The interaction intensity of parameters on TBM performance

The effect of the delay index on TBM performance

Although the relative intensity of interaction of each parameter can be obtained by engineering judgment, in order to define this relation with TBM performance the actual value of each parameter should be obtained.

The length of the tunnel is divided into 29 equal parts. TBM operation time and utilization coefficient are compared in each part (Table 4). Range of actual delays in hr/km for each part is very high and unlimited and converted to matrix ranking in order to data normalization as shown in table 5.

As the boring time (P1) is an index for evaluating the TBM performance, then unlike other parameters the actual value of this parameter has a positive impact on performance. Therefore, it could reduce by eliminating the interaction of the boring delays and problems identified. Although the actual values of some parameters are zero, because of the fact that C+E>0 all parameters from P2 to P18 affect the excavation time and eliminating of parameters are impossible.

The downtime index (DTI) calculated from equation 1 in this study (Hudson, 1992). This index shows the importance of the interaction of excavation delay in TBM performance.

$$\%\, a_i = \frac{1}{MP_{ij}} \times \frac{(C+E)}{\sum_i (C+E)} \times 100$$

$$DTI_J = \sum_{i=1}^{18} (a_i \times P_{ij})$$

Table 4. TBM excavation comparison at each tunnel parts

Tunnel Partition	Tunnel Chainage (m)		TBM advance (m)	TBM operation (day)	Utilization coefficient (%)
	From	To			
Part 1	133	1143	1010	81	23.0
Part 2	1143	2143	1000	53	24.7
Part 3	2143	3142	999	52	21.1
Part 4	3142	4135	993	42	24.7
Part 5	4135	5124	990	42	24.9
Part 6	5124	6136	1012	44	25.5
Part 7	6136	7133	997	42	24.1
Part 8	7133	8132	999	50	18.6
Part 9	8132	9136	1005	71	13.8
Part 10	9136	10148	1012	58	18.3
Part 11	10148	11150	1002	63	18.3
Part 12	11150	12138	988	66	20.2
Part 13	12138	13148	1010	59	19.0
Part 14	13148	14154	1006	77	14.7
Part 15	14154	15147	994	70	16.4
Part 16	15147	15847	700	46	17.0
Part 17	16166	17176	1010	105	12.2
Part 18	17176	18176	1000	65	19.7
Part 19	18176	19175	999	45	24.8
Part 20	19175	20168	993	46	23.4
Part 21	20168	21181	1013	43	22.7
Part 22	21181	22169	988	41	21.1
Part 23	22169	23166	997	47	19.4
Part 24	23166	24165	999	72	21.7
Part 25	24165	25170	1004	68	31.3
Part 26	25170	26182	1012	47	31.4
Part 27	26182	27183	1002	51	24.4
Part 28	27183	28172	988	46	27.7
Part 29	28172	29181	1009	53	25.6

Table 5. the actual value of parameters that affect the TBM performance in each section

	Mechanized tunnel partition																												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
P1	2.784	1.958	1.634	1.550	1.561	1.677	1.510	1.388	1.467	1.587	1.696	1.989	1.678	1.691	1.711	1.170	3.271	2.200	1.765	1.870	1.580	1.146	1.781	2.206	1.092	1.538	2.080	1.673	2.473
P2	0.382	0.384	0.386	0.381	0.379	0.388	0.378	0.388	0.385	0.380	0.381	0.384	0.383	0.385	0.380	0.268	0.234	0.194	0.191	0.190	0.199	0.195	0.190	0.192	0.192	0.194	0.192	0.200	0.192
P3	4.000	2.941	2.420	2.061	1.525	1.489	1.313	1.509	1.551	1.622	1.636	1.715	1.647	1.645	1.647	1.054	1.305	1.607	1.175	0.880	0.911	0.563	1.244	1.321	1.303	1.289	1.375	1.440	1.299
P4	2.355	1.648	1.560	0.729	0.945	1.063	0.877	1.209	1.724	1.419	1.163	0.919	1.295	1.350	1.084	0.758	3.232	1.983	0.892	1.063	1.059	0.888	1.061	1.731	1.708	0.774	0.906	0.867	1.045
P5	0.640	0.390	0.369	0.307	0.213	0.331	0.147	0.237	0.428	0.460	0.411	0.512	0.213	0.910	1.020	0.482	0.829	0.463	0.343	0.218	0.375	0.278	0.205	0.452	0.570	0.310	0.478	0.266	0.249
P6	0.121	0.257	0.336	0.278	0.316	0.145	0.171	0.365	0.607	0.563	0.424	0.637	0.453	0.385	0.414	0.081	0.257	0.364	0.232	0.382	0.196	0.195	0.293	0.663	0.620	0.296	0.516	0.360	0.472
P7	0.089	0.127	0.131	0.206	0.119	0.076	0.167	0.160	0.145	0.090	0.248	0.276	0.208	0.180	0.247	0.089	0.136	0.185	0.162	0.181	0.068	0.160	0.164	0.157	0.105	0.205	0.167	0.254	0.185
P8	0.690	0.254	0.304	0.238	0.386	0.334	0.406	0.475	0.425	0.430	0.357	0.546	0.479	0.468	0.507	0.263	0.832	0.289	0.339	0.405	0.302	0.320	0.571	0.462	0.464	0.304	0.483	0.233	0.417
P9	0.110	0.126	0.026	0.053	0.045	0.041	0.014	0.011	0.006	0.007	0.009	0.006	0.023	0.131	0.030	0.008	0.169	0.091	0.051	0.048	0.041	0.014	0.007	0.023	0.007	0.009	0.004	0.002	0.026
P10	0.317	0.167	0.191	0.132	0.068	0.163	0.079	0.096	0.088	0.211	0.100	0.274	0.471	0.468	0.286	0.109	0.448	0.230	0.210	0.042	0.195	0.080	0.089	0.096	0.211	0.100	0.075	0.395	0.378
P11	0.110	0.176	0.064	0.223	0.050	0.025	0.132	0.137	0.089	0.078	0.136	0.100	0.064	0.189	0.245	0.148	0.204	0.135	0.235	0.054	0.023	0.122	0.132	0.095	0.110	0.100	0.098	0.042	0.060
P12	3.152	0.856	0.652	0.748	0.982	0.932	1.263	1.207	1.208	0.758	0.811	0.935	0.637	1.238	0.217	0.079	3.603	0.865	0.717	1.089	0.859	1.304	1.205	1.307	0.862	0.626	0.842	0.607	0.707
P13	0.723	0.632	0.410	0.162	0.229	0.272	0.299	0.354	0.903	0.344	0.387	0.409	0.353	1.698	1.894	1.256	1.049	0.641	0.208	0.235	0.278	0.312	0.308	0.967	0.387	0.314	0.312	0.292	0.527
P14	0.744	0.247	0.297	0.240	0.197	0.313	0.068	0.213	0.113	0.097	0.089	0.093	0.127	0.163	0.080	0.054	0.913	0.337	0.263	0.182	0.344	0.056	0.202	0.140	0.111	0.084	0.072	0.082	0.145
P15	0.037	0.162	0.085	0.058	0.009	0.022	0.020	0.056	0.379	0.119	0.045	0.024	0.071	0.306	0.465	0.325	0.037	0.243	0.043	0.024	0.030	0.024	0.068	0.394	0.133	0.029	0.022	0.019	0.070
P16	0.253	0.263	0.212	0.139	0.194	0.284	0.325	0.226	0.286	0.199	0.288	0.182	0.000	0.973	1.760	1.384	0.354	0.342	0.144	0.216	0.233	0.342	0.268	0.296	0.236	0.230	0.212	0.001	0.063
P17	0.011	0.005	0.015	0.021	0.002	0.007	0.009	0.015	0.066	0.017	0.010	0.013	0.019	0.188	0.017	0.002	0.011	0.027	0.022	0.009	0.025	0.022	0.064	0.045	0.009	0.003	0.011	0.008	0.017
P18	0.257	0.121	0.040	0.027	0.113	0.014	0.037	0.011	0.199	0.033	0.020	0.165	0.192	0.263	0.137	0.122	0.304	0.120	0.030	0.103	0.031	0.037	0.032	0.206	0.046	0.004	0.086	0.233	0.104

																				Cause
Boring	**P1**	P1	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	4
Gripping / Move	**P2**	1	P2	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	3
Ring Building	**P3**	4	0	P3	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	6
Routine Maintenance	**P4**	3	3	3	P4	0	0	2	3	0	4	4	3	0	0	0	0	0	0	25
Cutter Check	**P5**	3	0	0	0	P5	4	0	0	0	0	0	0	0	0	1	0	0	0	8
Cutter change	**P6**	4	0	0	0	1	P6	0	0	0	1	0	0	0	0	0	0	0	0	6
VMT & Survey	**P7**	4	0	4	0	0	0	P7	0	0	0	0	0	0	0	0	0	0	0	8
Utility Service (water, air and power)	**P8**	4	4	4	4	3	3	3	P8	0	2	2	4	0	3	0	1	0	3	40
Lack of materials	**P9**	4	3	3	4	1	1	0	4	P9	2	2	3	0	3	0	2	0	0	32
Mechanical & Hydromechanical problems	**P10**	4	4	4	4	0	0	0	1	0	P10	0	2	0	2	0	1	0	0	22
Electrical problems	**P11**	4	2	4	4	0	0	0	1	0	2	P11	0	0	2	0	1	0	0	20
Transportation & Conveyor problems	**P12**	4	0	0	1	0	1	0	0	0	2	2	P12	3	2	0	2	0	3	20
Shift change	**P13**	4	4	4	4	4	4	4	4	1	2	2	4	P13	4	2	2	0	1	50
Ground improvement (Probe Drilling and Grouting)	**P14**	2	0	0	0	4	3	0	0	0	0	0	0	0	P14	0	0	4	0	13
Washing & Cleaning	**P15**	1	1	0	1	4	3	0	0	0	1	0	0	0	0	P15	0	0	0	11
Train exchange & unloading problems	**P16**	2	0	0	0	0	0	0	0	0	0	0	4	0	1	0	P16	0	0	7
Geological Problems	**P17**	4	4	4	0	4	4	0	0	0	0	0	2	0	4	4	0	P17	0	30
Lunch, safety meeting & Others	**P18**	1	0	0	1	0	0	0	1	0	0	0	2	1	0	0	0	0	P18	6
	Effect	53	26	31	23	21	23	9	14	1	19	15	24	4	21	7	9	4	7	

Where M and P_{ij} are maximum value of a parameter and actual time of delays in each part of tunnel respectively. DTI means downtime index that is the inverse relationship with the machine performance. Therefore, the utilization coefficient and TBM performance will decrease with increasing this index. According to fig. 6, the DTI has an unacceptable dependence with utilization coefficient (r^2=0.21). the coefficient of determination (r^2) is affected by the matrix component coding method and amount overlap of activities and delays.

In this project, the overlap effect of activities and delays is very prominent because. D.S.TBM designed to be able to perform multiple activities simultaneously during boring.

The advantage of DTI in evaluating the TBM performance can be observed in the TBM operation diagram in each part of the tunnel. If the TBM operating days in each part are considered as a measure of TBM performance, it is considered that the utilization coefficient has a weak relationship with the TBM operation relative to DTI. Because the utilization coefficient along with the penetration rate is effective in the TBM performance determination, which is referred to as the advance rate, however, DTI is based on delays and unlike the utilization coefficient, represents the performance of the TBM alone as shown in fig. 7.

In some geological conditions, such as very strong and good quality rocks, as well as crushed zones and unstable rocks, the penetration rate is significantly reduced, which results in an inverse relationship utilization coefficient with TBM performance. In crushed zones, TBM operators reduce the TBM parameters such as rotation speed and thrust force for safe passage of rock fall zone, leading to a significant reduction in penetration rate, while the utilization coefficient due to increasing boring time has grown dramatically (Tajik et al., 2010). Therefore, DTI has the same effect on TBM performance in any geological condition and tunnel progress can be easily managed by this parameter.

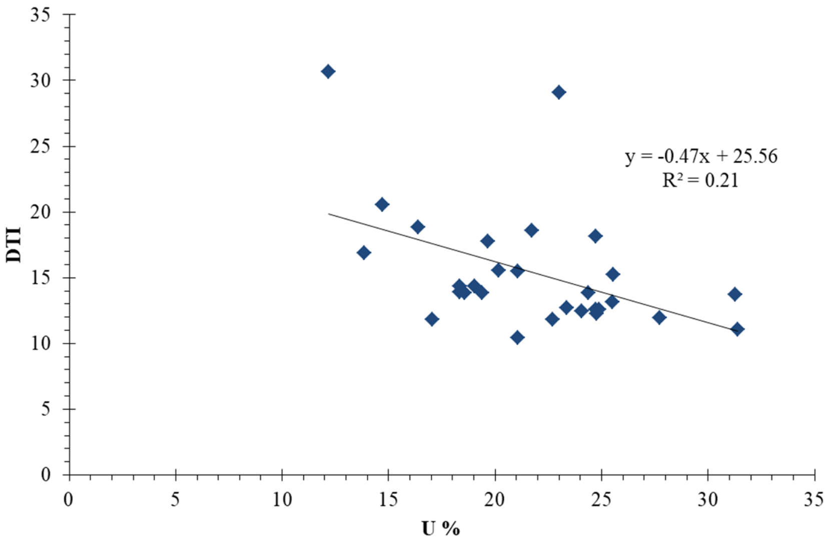


Figure 6. Relationship between DTI and TBM utilization coefficient in Karaj tunnel

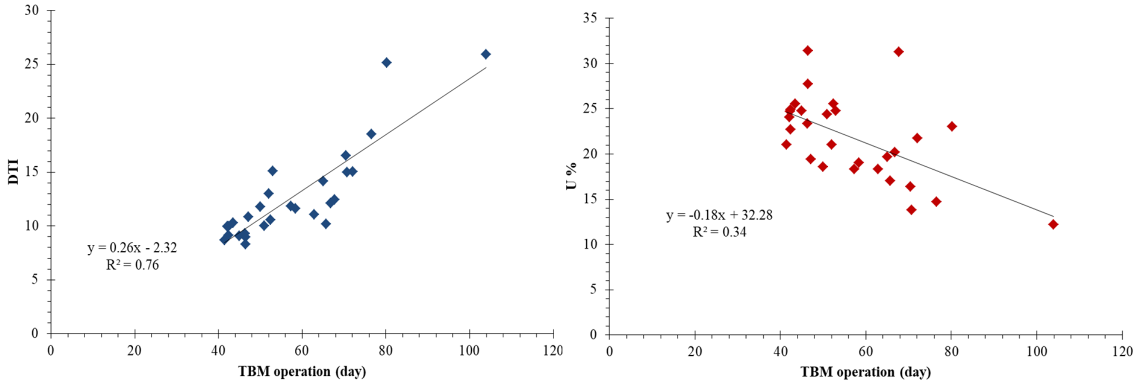


Figure 7. Relationship of TBM Operation Period with DTI and utilization coefficient

Conclusions

Obviously, the utilization coefficient is influenced by the delays in each activity. Therefore, in order to increase the utilization coefficient, it is necessary to reduce the number of delays. One of the simplest and most reliable methods for accessing a high utilization coefficient is to know the intensity of delays interaction by the matrix method. In the Karaj tunnel, the most effective parameters on the performance of D.S.TBM are utility services, shift change, and routine maintenance. Therefore, managing these parameters reduces the time of other delays and increases the utilization coefficient. The downtime index can be used as an indicator to compare the performance of TBM in different tunnels. The advantage of DTI is that by increasing it the factors known to reduce the advance rate are easily recognized and that delays and excavation problems can be resolved for the next parts of the tunnel.

Acknowledgements

The authors wish to thank Tarbiat Modares University for supporting this research and SAHEL consultant Engineers Institute for providing some reports.

References

Abd Al-Jalil, Y. Q., 1998. Analysis of Performance of Tunnel Boring Machine-Based System. PhD Thesis, the University of Texas.

Adesida, Patrick A., 2022. Powder factor prediction in blasting operation using rock geo-mechanical properties and geometric parameters. International Journal of Mining and Geo-Engineering, 56(1): 25-32.

Alsahly, A., Hegemann, F., Ko¨ nig, M., Meschke, G., 2020. Integrated BIM-to-FEM approach in mechanised tunnelling. Geomechanics and Tunnelling, 13(2): 212-220.

Azadmehr, A, Jalali, S.M., Pourrahimian, Y., 2019. An application of rock engineering system for assessment of the rock mass fragmentation: a hybrid approach and case study. Rock Mechanics and Rock Engineering, 52(11): 4403-4419.

Barton, N., 1999. TBM Performance Estimation in Rock Using QTBM. Tunnel & Tunneling International, 31(90): 30-34.

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

Benardos, A.G., Kaliampakos, D.C., 2004. Modelling TBM performance with artificial neural networks. Tunnelling and Underground Space Technology, 19(6): 597-605.

Bieniawski, Z.T., Celada, B., Galera, J.M., 2007. Predicting TBM Excavability. Tunnel & Tunnelling International, 25-28.

Bruland, A., 1998. Advance Rate and Cutter Wear, Hard Rock Tunnel Boring Machine. PhD Thesis, Trondheim Norwegian University of Science and Technology, NTNU 3.

Ceryan, N., Ceryan, S., 2008. An application of the interaction matrices method for slope, failure susceptibility zoning: Dogankent settlement area (Giresun, NE Turkey). Bulletin of Engineering Geology and the Environment, 67 (3): 375-385.

Farmer, I.W., Glossop, N.H., 1980. Mechanics of disc cutter penetration. Tunnels and Tunneling, 12 (6): 22-25.

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

Fattahi, H. 2018. An estimation of required rotational torque to operate horizontal directional drilling using rock engineering systems. Journal of Petroleum Science and Technology, 8 (1): 83-97.

Freitag, S., Cao, B.T., Ninic, J., Meschke, G., 2018. Recurrent neural networks and proper orthogonal decomposition with interval data for real-time predictions of mechanised tunnelling processes. Computers & Structures, 207: 258-273.

Frough, O., Khetwal, A., Rostami, J., 2019. Predicting TBM utilization factor using discrete event simulation models. Tunnelling and Underground Space Technology, 87: 91-99.

Frough, O., Torabi, S.R., Yagiz, S., Tajik, M., 2012. Effect of Rockmass Conditions on TBM Utilization Factor in Karaj - Tehran Water conveyance tunnel. World Tunneling Congress, Thailand.

Frough, O., Torabi, S.R., Ramezanzadeh, A., Yagiz, S., 2011. Influence of rock mass conditions on TBM downtime in Karaj water conveyance tunnel. First Asian and 9th Iranian tunnel symposium (Persian).

Gansser, A., Huber, H., 1962. Geological Observation in the Central Elburz, Iran. Schweizerische Mineralogische Und Petrographische Mitteilungen 42.

Gong, Q., Jiao, Y., Zhao, J., 2006. Numerical modeling of the effects of joint spacing on rock fragmentation by TBM cutters. Tunnelling and Underground Space Technology, 21(1):46-55.

Gong, Q.M., Zhao, J., 2009. Development of a rock mass characteristics model for TBM penetration rate prediction. International Journal of Rock Mechanics & Mining Sciences, 46 (1): 8-18.

Goodarzi, A., Hassanpour, J., Yagiz, S., Rostami, J., 2021. Predicting TBM performance in soft sedimentary rocks, case study of Zagros mountains water tunnel projects. Tunnelling and Underground Space Technology, 109: 103705.

Graham, P.C., 1976. Rock exploration for machine manufactures, Proceedings Symposium on Exploration for Rock Engineering, Johannesburg.

Hashemnejad, A., Fatemi Aghda, S.M., Talkhablou, M., 2020. Mechanized tunnelling in hydrothermally altered grounds: The effect of hydrothermal fluids on the rock behaviour in the central Iran. Tunnelling and Underground Space Technology, ID: 216303248. 10.1016/j.tust.2020.103340

Hassanpour, J., Rostami, J., Khamhechiyan, M., Tavakoli, H.R., 2009. "TBM Performance Analysis in Pyroclastic Rocks: Case History of Karaj Water Conveyance Tunnel. Rock Mechanics and Rock Engineering Journal, 43:427-445.

Hudson, J.A. 1992. Rock Engineering Systems, Theory and Practice. Ellis Horwood, Chichester.

Hudson, J.A., Harrison, J.P., 1997. Engineering rock mechanics an introduction to the principles. Pergamon.

Innaurato, N., Mancini, R., Rondena, E., Zaninetti, A., 1991. Forecasting and effective TBM performances in a rapid excavation of a tunnel in Italy. Proceeding of 7th International Congress on Rock Mechanics, 1009-1014.

KhaloKakaie, R., Zare naghadehi, M., 2009. The analysis and classification of rock slopes instability potential in Khosh - Yeylagh mountainous road using systems approach (In Persian). Journal of Iranian Association of Engineering Geology, 2 (1,2): 19-32.

KhaloKakaie, R., Zare naghadehi, M., 2012. The assessment of rock slope instability along the Khosh-Yeylagh Main Road (Iran) using a systems approach. Environmental Earth Sciences, 67 (3): 665-682.

Mahmoodzadeh, A., Mohammadi, M., Daraei, A., Ali, H.F.H., AlSalihi, N.K., Omer, R.M.D., 2020. Forecasting maximum surface settlement caused by urban tunneling. Automation in Construction, 120: 103375.

Moosazadeh, S., Aghababaie, H., Hoseinie, S.H., Ghodrati,B., 2018. Simulation of tunnel boring machine utilization: A case study. Journal of Mining & Environment, 9 (1): 53-60.

Nelson, P., O'Rouke, T.D., Kulhawy, F.H., 1983. Factors affecting TBM penetration rates in sedimentary rocks. 24th U.S. Symposium on Rock Mechanics.

Ninic, J, Bui, H.G., Meschke, G., 2020. BIM-to-IGA: A fullyautomatic design-through-analysis workflow for segmented tunnel linings. Advanced Engineering Informatics, 46: 101137.

Ninic, J., Freitag, S., Meschke, G., 2017. A hybrid finite element and surrogate modelling approach for simulation and monitoring supported TBM steering. Tunnelling and Underground Space Technology, 63: 12-28.

Palmstrom, A. 1995. RMi Parameters Applied In Prediction of Tunnel Boring Penetration. In: A. Palmtrom, RMi - A Rock Mass Characterization System for Rock Engineering Purposes (Chapter7), PhD Thesis, Oslo University, Norway.

Ramezanzadeh, A., Rostami, J., Kastner, R., 2002. Performance Prediction Models for Hard Rock Tunnel Boring Machines. The 6th Iranian Tunneling Conference .

Ramezanzadeh, A., 2005. Performance analysis and development of new models for performance prediction of hard rock TBMs in rock mass. PhD Thesis, Lyon: Institute National des Sciences Appliqu´ees.

Rostami, J, Ozdemir, L., 1993. A new model for performance prediction of hard rock TBMs. RETC conference proceedings, Boston.

Rostami, J., Ozdemir, L., Nilson, B., 1997. Comparison between CSM and NTH Hard Rock TBM

Performance Prediction models. Colorado School of Mines, Golden, Colorado, USA.

Roxborough, F.F., Phillips, H.R., 1975. Rock excavation by disc cutter. International Journal of Rock Mechanics and Mining Sciences, 12(12): 361-366.

Rozos, D., Pyrgiotis, L., Skias, S., Tsagaratos, P., 2008. An implementation of rock engineering system for ranking the instability potential of natural slopes in Greek territory. An application in Karditsa County. Landslides, 5: 261-270.

Sadeghi, M., Rasouli, V., 2011. application of rock engineering systems in evaluation of stability of underground excavations. Amirkabir Journal of Civil Engineering, 43(1): 89- 95.

SAHEL consultant engineers institute, 2011. Engineering Geology As built Maps and Site Reports of Conveyance Tunnel (Lot 2). SCE Archive.

SAHEL consultant engineers institute, 2009. Engineering Geology Report of Karaj-Tehran Water Conveyance Tunnel (Lot 2). unpublished report.

Sanio, H.P., 1985. Prediction of the Performance of Disc Cutters in Anisotropic Rock. International Journal of Rock Mechanics and Mining Sciences & Geomechanics, 22(3): 153-161.

Sapigni, M., Berti, M., Bethaz, E., Busillo, A., Cardone, G., 2002. TBM performance estimation Using Rock mass Classification. International Journal of Rock Mechanic and Mining Sciences, 39(6):771-788.

Sato, K., Gong, F., Itakura, K,. 1991. Prediction of Disc Cutter Performance using a Circular Rock Cutting Ring. 1st International Mine Mechanization and Automation Symposium.

Simoes, M.G., Kim., T., 2006. Fuzzy Modeling Approaches for the Prediction of Machine Utilization in Hard Rock Tunnel Boring Machines. Conference Record of the 2006 IEEE Industry Applications Conference Forty-First IAS Annual Meeting, 2: 947-954.

Snowdon, A.R.D., Ryley, M., Temporal, J., 1982. Study of Disc Cutting in Selected British Rocks. International Journal of Rock Mechanics and Mining Science & Geomechanics, ID: 140586186.

Tajik, M., Oruji, M., Novin, A., 2010. Assessment of TBM performance in tunnel excavation, first lot of Karaj - Tehran water conveyance tunnel . Journal of Iranian Association of Engineering Geology, 3(1, 2): 41-50.

Tarkoy, P.J. 1975. Rock hardness index properties and geotechnical parameters for predicting tunnel boring machine performance. PhD Thesis, University of Illinois at Urbana-Champaign.

Xiao, H., Yang, W., Hua, J., Zhang, Y., Jing, L., 2022. Significance and methodology: Preprocessing the big data for machine learning on TBM performance. Underground Space, 7(4): 680-701.

Xu, C., Liu, X.L., Wang, E.Z., Wang, S.J., 2021. Prediction of tunnel boring machine operating parameters using various machine learning algorithms. Tunnelling and Underground Space Technology, 109: 103699.

Yaghoubi, 2010. prediction of TBM performance by rock engineering systems method. Thesis for M.Sc. Degree, University of Kerman (Persian).

Yagiz, S. 2008. Utilizing rock mass properties for predicting TBM performance in hard rock condition. Tunnelling and Underground Space Technology, 23(3):326-339.

Yavari, F., Mansoori, H., Ebrahimi, M.A., 2011. Determination of TBM advance rate by rock engineering systems. First Asian and 9th Iranian tunnel symposium (Persian).

Zare Naghadehia, M., Samaei, M., Ranjbarnia, M., Nourani, V., 2018. State-of-the-art predictive modeling of TBM performance in changing geological conditions through gene expression programming. Measurement, 126: 46-57.

Zhang, L.Q., Yang, Z.F., Liao, Q.L., Chen, J., 2004. An application of the rock engineering system (RES) methodology to rockfall hazard assessment on the Chengdu-Lhasa Highway, China. International Journal of Rock Mechanics & Mining Sciences, 41(3): 526-527.