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Evaluation of TBM utilization using rock mass rating system: a case study of Karaj-Tehran water conveyance tunnel (lots 1 and 2)

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Abstract
Successful application of a TBM in a project requires investigating both the ground conditions and the machine and backup system design features. Prediction of the machine performance is very important as it has a big effect on the duration of the project and the costs. In this respect, both penetration rate and advance rate must be estimated. Utilization factor, which depends on the type of operation, management, maintenance, geological conditions, mucking delays and other downtimes, correlates the advance rate and penetration rate. Adverse rock mass conditions such as mixed face condition, water problem and instability of rock have a great role in TBM downtimes and reduce the machine utilization considerably. Based on detailed engineering geological reports and maps and daily site reports taken from Karaj-Tehran Water Conveyance Tunnel (Lots 1 and 2), this paper evaluates, main rock mass properties utilized for the estimation of TBM performance and discusses their effect on the machine utilization. . More specifically it uses the developed database also contains daily boring time, different rock mass related downtimes, daily advance and length of bored tunnel in each engineering geological units. It is concluded that the percentage of the rock mass related downtimes can be estimated via RMR within reliable coefficient of determination.

Keywords: *Ground conditions, RMR, Utilization, TBM downtimes, Karaj water conveyance tunnel*.

1. Introduction

Successful application of a TBM in a project requires investigations both of the ground conditions and of the machine and backup system design features. Utilization factor (U), which is highlighted in this research work, affecting the total duration of the activity, determines the advance rate. In a mechanized tunneling project, it is necessary to predict TBM performance for estimation of the project duration and costs. In prediction of the machine performance, both penetration rate (ROP) and advance rate (AR) must be estimated (AR=ROP×U). ROP is defined as the distance excavated divided by the operating time during a continuous excavation phase, while AR is the actual distance mined and supported divided by the total time. There has been a lot of research on the development of models to allow accurate prediction of machine rate of penetration in given ground conditions.

A wide variety of performance prediction models and principles are used in different countries. Some of these methods are based mainly on parameters of rock, such as uniaxial compressive strength and rock abrasion value, while others are based on a combination of comprehensive laboratory, field and machine data.

The AR is calculated using an estimate of the ROP and machine utilization factor. Machine utilization is the percentage of time the machine is excavating out of the total project time. U basically depends on the type of operation, management, maintenance of machine, geological conditions, capacity of the backup system and other factors, which can introduce downtimes to the operation. TBM downtimes generally include the times of support installation, re-gripping, grouting, maintenance, machine break down, cutter change, mucking delays, geological adverse conditions and others such as shift changes and lunch breaks [1]. Adverse rock mass conditions reduce U because of TBM rock mass related down times such as ground improvement, support installation, cutter changing, dewatering etc.

Most of the prediction models have considered only PR. Models such as CSM, NTNU and Q_{TBM} have been developed for predicting TBM performance and have suggested some relationships and graphs for estimating U.

2. TBM performance prediction models

The prediction models are divided into two main categories: theoretical/experimental and empirical models. The basic philosophy of theoretical/experimental models is the determination of the individual cutter forces and the overall thrust, torque and power requirements of the entire cutterhead. The estimated values are then compared with the installed machine or available thrust and power so as to obtain the maximum achievable penetration.

Many researchers have developed different TBM performance prognosis models and principles. Graham estimated the penetration rate of TBM by uniaxial compressive strength of intact rock in 1976 [2]. Farmer and Glossop suggested a relationship between Brazilian tensile strength and penetration rate in alluvial rocks in 1980 [3]. Cassinelli determined the penetration rate of TBM by use of RSR in 1982 [4] and Innaurato et al. developed a strong relationship between RSR, UCS and penetration rate of TBM in 1991 [5]. Snowdon et al. and Sanio suggested relationships between rock compressive strength and the specific energy in 1983 and 1985 respectively [6 ,7]. CSM model was developed at Colorado School of Mines by Ozdemir et al. in 1977 and was updated by Rostami in 1993 and 1997 [8, 9]. Later in 1999 Cheema offered some modifications on CSM model [10]. In1995, Palmstrom introduced a prediction model base on Rock Mass index [11]. NTNU model was developed at Trondheim Norwegian University of Science and Technology [12]. Q_{TBM} model was developed by Barton in 2000 based on expanded Q system [13]. Rock Mass Rating parameters are also used for estimating TBM performance by Sapigni et al.,; Bieniawski, 2007; Hamidi et al., 2010 [14,15,16]. In 2008, Yagiz introduced a relationship between rock mass properties and PR [17]. Influence of rock mass characteristics on TBM performance, mainly from the point of view of penetration rate, has been investigated by many researchers. Hassanpour et al. suggested relationships between rock mass properties and field penetration index in 2010 [18] suggested relationships based on particle swarm optimization for the prediction of penetration rate in 2011 [19].

Other researchers developed methods such as artificial neural network (ANN) and fuzzy logic predicting performance models with respect to the geological and geotechnical site conditions [20 ,30]. Also two-dimensional numerical analyses were performed to explore the effect of joint orientation and joint spacing on rock fragmentation by a TBM [21,22].

3. Effect of rock mass conditions on utilization factor

Different rock mass conditions have different effects on TBM operation and each effect may reduce machine utilization. Previous findings show that geological adverse conditions have a great role in TBM downtimes. In such conditions, average utilization factor in projects is 30% maximum utilization being about 40% and downtimes related to geological conditions is about 15% [23]. If cutter change downtimes were considered, rock mass and geology related downtimes would increase [24].

The main causes of cutter wear are the presence of quartz and other abrasive minerals in rock and operating in mixed face conditions. Instability and collapses cause long downtime due to the necessity of ground improvement and rock cleaning. Similarly groundwater has a great roll in delay in tunnel boring operations. Presence of clay and sticky minerals is another reason of downtimes due to the issues of cutter head cleaning and mucking problems. Existence of poisonous gases like methane and H_2S can also cause delays and downtimes by decreasing the crew performance, damaging electronic devices and demanding extra ventilating. Table 1 shows the mode of effect on utilization factor by rock mass conditions.

4. Karaj-Tehran water conveyance tunnel

The 30-kilometer Karaj-Tehran water conveyance tunnel is located in northwest of Tehran ,capital city_of Iran, between Karaj and Tehran. It was designed to transfer 16 m^3/s of water from Amir-Kabir dam to Tehran. figure 1 shows the location of the tunnel.

Table 1. Parameters affecting downtimes and utilization percentage of excavated tunnel [24]

Parameter	Direct effect/problem	Indirect effect/reason for downtime
Instable/collapsed tunnel	Ground improvement	Increase of support installation time
Rock abrasion	Cutter wear	Time to replace the cutters
Discontinuities	Cutter head locking	Time to release cutter head
Groundwater	Time to Dewatering/water tightening	Increase of support installation time and decreasing utilization percentage
Clay and sticky materials	clogging	Increase of mucking time, Cutter head cleaning
Squeezing	Shield locking	Time to release TBM
Mixed face condition	Sudden collapse	Cutter malfunction
Poisonous gas	Extra ventilation	Decrease of crew performance

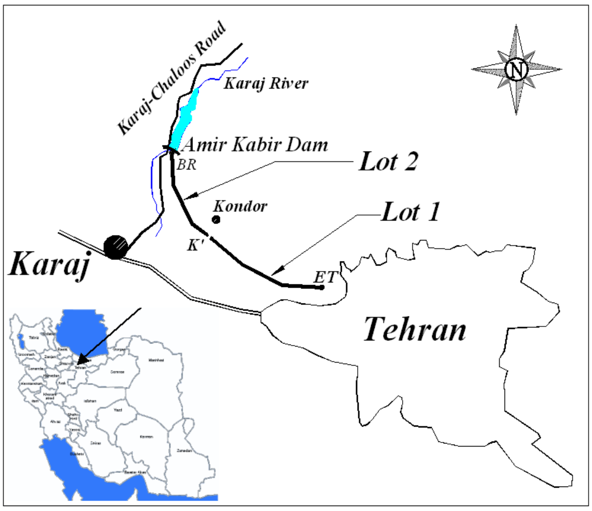

Figure 1. Location of the Karaj-Tehran water conveyance tunnel.

The tunnel is divided into two sections: Lot 1 or ET-K` (16 km) at the southeast end and Lot 2 or K`-BR (14 km) at the northwest end of the project area. The first Lot of the tunnel was excavated and lined using a Double Shield TBM. The basic specifications of the TBM are shown in table 2. Lot 2 is also being excavated and lined by this TBM after overhauled. By November 2011, about 11 kilometers of 14-kilometer Lot 2 tunnel was excavated and lined. Boring diameter of tunnel is 4.66 m and final diameter of tunnel is 3.90 m. The tunnel is lined with pre-cast concrete segments with tetragonal arrangement (5+key) and a thickness of 25 cm.

This study made use of the detailed engineering geological reports, the maps and the daily site reports- used in the project. The collected data consists of boring times, different downtimes and their causes and machine data such as applied thrust, torque and RPM that were recorded on a daily basis. Developed database also contains daily boring time, different rock mass related downtimes, daily advance and length of bored tunnel in each engineering geological units.

Table 2. Specifications of TBM utilized for Karaj-Tehran project [25]

Machine diameter (m)	4.66
Cutters diameter (mm)	432
Cutter disk spacing (mm)	70
Number of cutters	31
Cutterhead power (KW)	1250
Cutter headspeed (RPM)	11
Cutterhead torque (kN-m)	2500
Max cutterhead thrust (kN)	17,000

4.1. Tunnel Lot-1

At the ET portal, a double shield TBM was launched from a 140 m starting tunnel excavated by conventional methods (Roadheader). The elevation of K` and ET points at the two ends of the section are 1582 m and 1560 m MSL respectively, obtaining a slope of 0.137% toward the outlet portal. The maximum overburden in Lot-1 is 670 m, with an average of about 400 m. The site preparation started in 2004 and the TBM installation began on May 2006 and was finished in about 3 months. TBM tunneling of Lot 1 started in August 2006 and finished in June 2009.

4.1.1. Geology (Lot-1)

The lithology of this area consists of a sequence of Karaj formations and is composed of various pyroclastic rocks, often interbedded with sedimentary rocks. The characteristic rock type is a green vitric to crystal lithic tuff, tuff breccias, sandy and silty tuffs with shale, siltstone and sandstone [18]. The engineering geological profile of the tunnel is shown in figure 2. In the project area, 14 predominant stratigraphic units were identified along the tunnel alignment (U1 to U14). The formations, which are classified into 9 engineering geological units, are listed in table 3.

4. 1. 2 Tunnel operation (Lot-1)

The length of Lot-1 is 16042 meters. About 140 meters of the beginning and 190 meters of the end of the tunnel were excavated by conventional methods. The daily maximum ROP was 7.3 m/h,maximum AR was 38.9 m/day and maximum utilization factor was 53.8%. Average ROP was 3.32 m/h and average advance rate was 15.4 m/day.

The developed database contains daily boring time, different rock mass related downtimes, daily advance and length of bored tunnel in each engineering geological unit of 1016 days of operation (15684 meters of tunnel from chainage 158 to 15842).

Different geological units appear in different lengths along the tunnel. To achieve more realistic judgment of time distribution among them, downtimes were calculated in hour per unit length of tunnel in different units. Average time distribution of tunneling activities is shown in figure 3. In this figure, other relevant downtimes are total delays related to maintenances, transportation, washing and cleaning, utility installation and shift change (non rock mass related downtimes). Table 4 shows geological and rock mass related downtimes (GRRD) and other relevant downtimes (ORD) for each rock unit and average time consumption along the tunnel for all rock units [24].

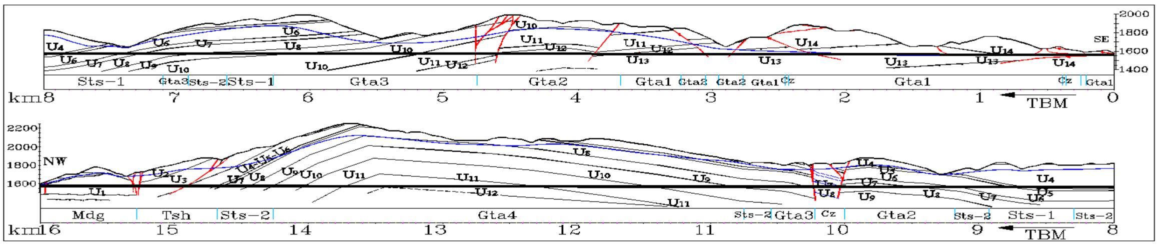

Figure 2- Engineering geological profile of tunnel Lot-1 [26].

Table 3. Engineering geological units encountered along the tunnel alignment [18,27]

Geological Units	Length (m)	RMR	Groundwater Condition	Remarks on rock properties and descriptions
Gta1-1	1334	35	dry	Weak to moderately strong rock, thin to moderately bedded, fractured, may be unstable
Gta1-2	1475	50	dry	Moderately strong rock, thin to moderately bedded, fractured, may be unstable
Gta2	2255	49	damp to wet	Moderately strong, thick to moderately bedded, moderately fractured, stable
Gta3	1784	64	damp to wet	Moderately strong, thick to moderately bedded, moderately fractured, stable
Gta4	3514	75	damp to wet	Very strong thick to moderately bedded, stable
Sts1	1790	57	partially flow	Weak to moderately strong rock, thin to moderately bedded, fractured, may be unstable
Sts2	1762	72	damp to wet	Very strong, thick bedded, stable
Mdg	507	63	wet	Moderately strong, thick to moderately bedded, moderately fractured, stable
Tsh	682	46	wet	Weak to moderately strong rock, thin -moderately bedded, foliated, fractured, may be unstable
Cz	581	21	damp to wet	Very weak strength, unstable rock

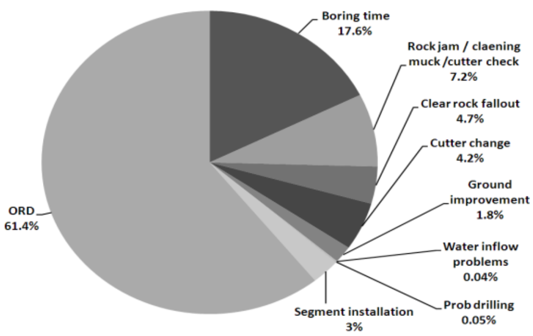

Figure 3. Average time consumptions as percentage for tunneling (Lot-1).

Table 4. Computed Utilization (U %), Geological and rock mass related downtime (GRRD) and other relevant downtimes (ORD) for each rock units and averaged time consumption along the tunnel Lot-1 [25]

Geological Units	RMR	Boring time (%)	GRRD (%)	ORD (%)
Gta1-1	35	23	21	56
Gta1-2	50	21	11	68
Gta2	49	21	17	62
Gta3	64	22	27	51
Gta4	75	16	22	62
Sts1	57	16	18	66
Sts2	72	17	17	66
Mdg	63	16	10	74
Tsh	46	16	13	71
Cz	21	9	53	38

As it can be seen in figure 3, average utilization factor achieved is about 18% (Net boring) and geology and rock mass related downtimes reached about 21%. The biggest downtime is attributed to cutter head and rock fall cleaning that relates to tunnel instability. Table 4 shows that most of the downtimes occurred in crushed rocks and faulted zones with low rock mass rating [24]. According to this table, the lowest GRRD was achieved in Gta1-2 and Mdg (RMR = 50 & 63). The highest GRRD was achieved in Cz unit (RMR = 21). The greatest downtimes are attributed to ORD problems.

4.2 Tunnel Lot-2

At the K` portal, TBM was launched from a 133 m starting tunnel which excavated by conventional methods (drill and blast). The maximum overburden in Lot-2 was 820 m, with an average of about 350 m. After site preparation, excavation began in November 2009. By November 2011, the excavated and lined length of tunnel achieved 10639 meter of 13470.8 meter.

4. 2. 1 Geology (Lot-2)

The lithology of this area consists of a sequence of Karaj formations and is composed of various pyroclastic rocks, often interbedded with sedimentary rocks. The characteristic rock type in this section is gray tuff, siltstone, sandstone, monzodiorite and monzogabro. The engineering geological profile of tunnel is shown in figure 4. In the project area, 15 predominant stratigraphic units were identified along the tunnel alignment. The engineering geological units encountered along the tunnel alignment in excavated area are listed in table 5.

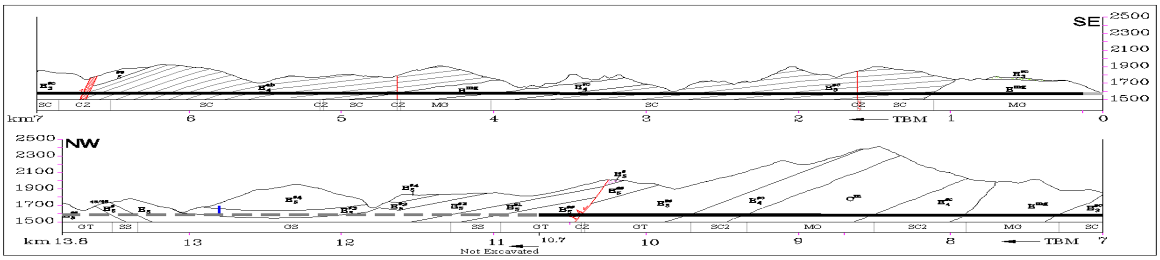

Figure 4. Engineering geological profile of tunnel Lot-2 [28].

Table 5. Engineering geological units encountered along the tunnel alignment in excavated area [28, 29]

Geological Units	Length (m)	RMR	Groundwater Condition	Remarks on rock properties and descriptions
MG	3844	67	Dry to wet	Strong, thick bedded, stable
SC	3901	40	Dry to wet	Thin to moderately bedded, fractured, may be unstable
SC2	269	45	damp to wet	Thin to moderately bedded, fractured, may be unstable
MO	837	67	dry to dripping	Strong, thick bedded, stable
GT	1027	50	damp to flow	Strong, thick bedded, almost stable
Cz2	381	30	Dripping to flow	Very weak strength, unstable rock

4. 2. 2 Tunnel operation (Lot-2)

The length of Lot-2 is 13800 meters and 133 meters of the beginning were excavated by conventional methods. By July 2011 about 10700 meter of tunnel was excavated. The daily maximum ROP was 6.63 m/h; maximum AR was 39.03 m/day and maximum utilization factor was 52.01%. Average ROP was 2.77 m/h and average AR was 15.6 m/day.

The developed database contains (same as database of Lot-1) 682 days of operation (10639 meters of tunnel from chainage 135 to 10700). Average time distribution of tunneling activities is shown in figure 5 and geological and rock mass related downtimes (GRRD) and other relevant downtimes (ORD) for each rock unit and average time consumption along the tunnel for all rock units are shown in table 6.

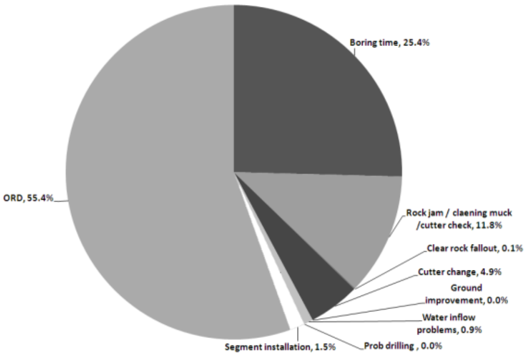

Figure 5. Average time consumptions as percentage for tunneling (Lot-2).

Table 6. Average time distribution in different geological units (Lot-2)

Geological Units	RMR	Boring time (%)	GRRD (%)	ORD (%)
MG	67	16	14	70
SC	40	19	19	62
SC2	45	29	19	52
MO	67	25	18	57
GT	50	28	17	55
Cz2	30	24	16	60

related downtimes reached about 20%. The biggest downtime is attributed to cutter head cleaning. Table 6 shows that rock mass related downtimes in different geological units are approximately between 14 to 19 percent. The greatest downtimes are attributed to ORD problems. In this tunnel such problems as squeezing, swelling, and poisonous gases did not exist the same as Lot 1, but ground water flow exists in this Lot to some extent.

4. 3 Comparison of the two tunnels downtimes

Tunnel Lot 1 and Lot 2 are located in different types of rock masses and the their time consumptions are reasonably similar. The performance parameters of tunnel Lots 1 and Lot 2 are compared in table 7.

Table 7. Comparison of performance parameters of tunnels Lot 1 and Lot 2

Tunnel	Boring time (%)	GRRD (%)	ORD (%)	Average ROP (m/h)	Average AR (m/day)
Lot 1	18	21	61	3.32	15.4
Lot 2	25	20	55	2.77	15.6

Considering that about 8% of tunnel length in Lot 1 was excavated in rock mass with RMR less than 25, the instability and collapses downtimes reached about 5 percent while in Lot 2 minimum RMR was 30 in about 4% of the tunnel length. That is why this type of downtimes in Lot 2 was limited to less than 1 percent. Also in Lot 2 down times related to ground improvement and probe drilling did not occur. In Lot 2, because of water inflow problems, downtimes related to cleaning and water flow was 5% more than Lot 1 and boring time was 7.8% more than that in Lot 1 but average ROP was less than Lot 1. Consequently, average AR was slightly greater in Lot 2.

5. Relation between RMR and downtimes

Rock mass properties and corresponding machine performance parameters were considered and evaluated through analysis of field shift reports and site investigation. There are 14 types of RMR in total 26323 meter of tunnels. In table 8 the time consumptions and ROP, AR and utilization factor of TBM in different rock masses are shown based on RMR. As it can be seen, the minimum utilization factor was achieved in RMR 21 and maximum in RMR 45 (8% and 28.71%). The minimum and maximum ROP were achieved in RMR 45 and 57 respectively. The maximum geology and rock mass related downtimes occurred in RMR 21 that is mostly related to stability problems. In average, about 25% of downtimes were related to geology and rock mass conditions.

Using available data, i.e. summery of about 26 km tunnels long (table 8), descriptive statistical results of which are given in Table 9, the relationship between rock mass rating and TBM performance parameters were examined through regression analysis. In this statistical approach, RMRs were input as independent variables and the measured ROP, U, AR and GRRD were input as dependent variables. Consequently, obtained machine performance parameters are listed and correlated with RMR to develop possible relationships between variables herein.

Table 8. The performance parameters of tunnels Lot 1 and Lot 2 based on RMR

No.	RMR	Length (m)	Ave. ROP (m/h)	Ave. AR (m/h)	U (%)	GRRD (%)
1	21	581.27	3.235	6.84	8.81	53.59
2	30	381.12	2.892	15.88	22.87	21.45
3	35	1333.58	3.563	13.37	15.63	12.90
4	40	3901.18	3.860	19.78	21.36	16.59
5	45	648.65	3.016	17.26	23.84	13.22
6	46	681.78	4.582	17.72	16.12	17.73
7	49	2255.3	4.009	14.93	15.51	10.14
8	50	2502.28	3.874	20.04	21.55	27.41
9	57	1790.11	3.879	15.73	16.90	16.62
10	63	507.46	3.515	13.67	16.20	21.76
11	64	1783.59	3.096	12.86	17.31	15.04
12	67	4681.05	3.353	15.36	19.08	18.83
13	72	1762.03	2.477	17.07	28.71	19.57
14	75	3513.63	3.745	21.17	23.56	16.05
average			3.51	15.83	19.10	20.06

Table 9. Descriptive statistical analysis of TBM performance, RMR, GRRD and utilization

	No of data	Minimum	Maximum	Mean	Std. Deviation
RMR	14	21	75	51	16.18
ROP (m/h)	14	2.48	4.58	3.51	0.54
AR (m/d)	14	6.84	21.17	15.83	3.62
U (%)	14	8.81	28.71	19.10	4.93
GRRD (%)	14	10.14	53.59	20.06	10.57

Various regression equations and relations were developed and some meaningful significant relationships were obtained among the known and unknown variables. In this study the statistical package SPSS 15 (2006) was used for conducting the analysis. The program was used to generate different models–, but no significant relationship between RMR and ROP, U and AR was achieved. It means that ROP, U and AR are related to some other parameters too. As an example, U depends on TBM and back up maintenance, machine break down, logistic, surveying and shift changes delays in addition to rock mass related downtimes. In case of RMR and GRRD, the maximum squared correlation coefficient (R^2 = 0.64) was obtained in Quadratic method (tables 10 ,11. The corresponding graph is shown in figure 6 and the resulting equation is as follow.

$$GRRD = 0.027\ RMR^2 - 2.932\ RMR + 93.907\ (R^2 = 0.64)$$

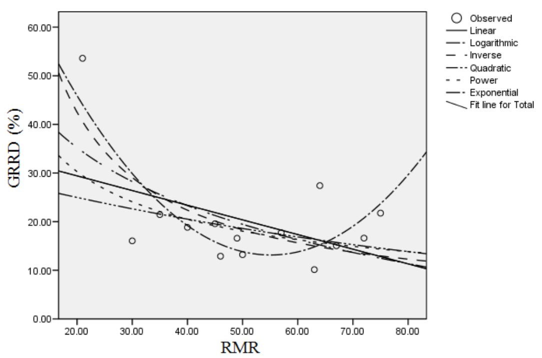

Figure 6. Relationships between GRRD and RMR.

Table 10. Variables and summary of the generated regression analysis

Equation	Dependent Variable	R Square	R Square adjust	Sig.
Linear	ROP	0.117	0.044	0.23
	AR	0.021	0.060	0.618
	U	0.004	0.079	0.823
	GRRD	0.213	0.148	0.096
Logarithmic	ROP	0.106	0.032	0.25
	AR	0.068	0.009	0.367
	U	0.004	0.079	0.835
	GRRD	0.348	0.294	0.026
Inverse	ROP	0.83	0.007	0.316
	AR	0.147	0.076	0.176
	U	0.042	0.037	0.48
	GRRD	0.507	0.466	0.004
Quadratic	ROP	0.117	0.043	0.503
	AR	0.338	0.218	0.103
	U	0.34	0.22	0.102
	GRRD	0.636	0.57	0.004
Power	ROP	0.099	0.24	0.273
	AR	0.151	0.08	0.170
	U	0.041	0.039	0.486
	GRRD	0.268	0.207	0.058
Exponential	ROP	0.114	0.040	0.237
	AR	0.068	0.009	0.367
	U	0.004	0.079	0.821
	GRRD	0.162	0.092	0.153

Table 11. Variables in the equation (GRRD)

Variable	B	SE B	Beta	T	Sig.
RMR	-2.932	0.746	-4.490	-3.932	0.002
RMR2**	0.027	0.007	4.081	3.573	0.004
(Constant)	93.907	17.546		5.352	0.000

The comparison between the measured and the predicted GRRD is shown in figure 7. Using an introduced equation, the reliable relationship between the predicted and the measured GRRD were achieved with an R = 0.797.

The analysis of residuals were applied for validating the regression model. For the residual analysis, different types of residual plots were used to check the validity of these. Residual plots such as histogram of the residuals, residual vs. predicted value and residual vs. independent can be used to assess the quality of a regression. For example, the scatter plot of the residuals will be disordered if the regression is good. The residuals should not show any trend. A trend would indicate that the residuals were not independent. On the other hand, a histogram plot of the residuals should exhibit a symmetric bell-shaped distribution, indicating that the normality assumption is true. The results are shown in figure 8.

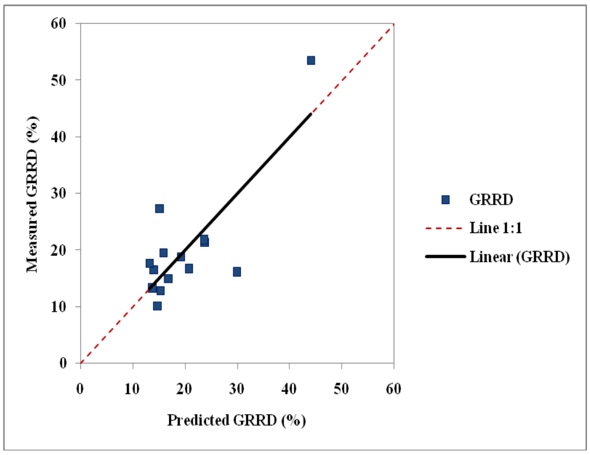

Figure 7. Linear relation between measured GRRD and predicted GRRD (R=0.797).

6. Conclusions

Utilization factor depends on operation management, tunnel geometry and rock mass conditions, the latter includes different factors. The greatest downtimes are related to non-rock mass related problems. Adverse rock mass conditions have great effects on TBM operations usually resulting in extra activities such as cutter head cleaning of rock falls, dewatering, frequent disc cutter changing and support installation. These activities reduce the machine utilization.

Data obtained from the 16-km long Karaj tunnel Lot-1 and 11-km long tunnel Lot-2 was used to estimate the GRRD as a function of Rock Mass Rating values. Geological units of this area comprise a sequence of Karaj formations having various pyroclastic rocks, often interbedded with sedimentary rocks. The influence of rock mass related downtimes on TBM performance and utilizations were examined. It was found that geology and rock mass related downtimes were about 20% in both tunnels. The highest utilization factor and advance rate are achieved in RMR 45 to 65. The relationship between GRRD and RMR shows a reasonable squared coefficient of correlation (R^2) of 0.64.

It can be concluded that in situations where abrasive minerals such as quartz exist, causing cutter wear, and/or clay and sticky minerals exist causing clogging and mucking problems, or there is mixed face condition resulting in cutter malfunctioning and collapses and finally there are poison gasses causing problems, the effect of rock mass parameters on TBM downtimes should be considered carefully. In this respect the important impact of machine utilization on project duration and costs is highlighted.

It is necessary to develop a rock classification system such as Modified Rock Mass Rating system in which, in addition to the existing items, the above mentioned parameters (abrasive minerals, sticky materials, poisonous gases, etc.) are included. This can strengthening the relationship between the TBM utilization and the proposed Rock Mass Rating Values.

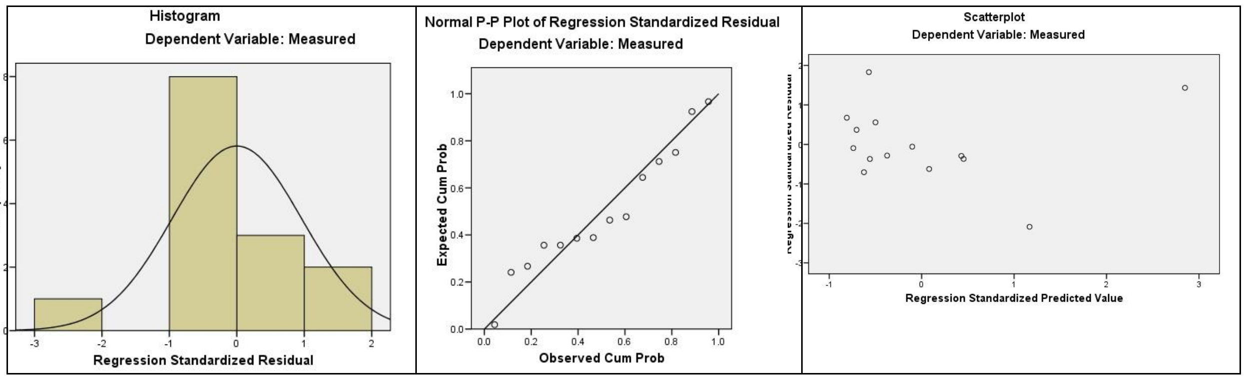

Figure 8. Results of residuals plots.

7. Acknowledgements

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