Analysis of TBM Performance in Two Long Mechanized Tunnels, Case History of Karaj Water Conveyance Tunnel Project Lots 1 and 2 (Iran)

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ABSTRACT: Analysis and assessment of TBM performance during construction and comparing the field performance with the predicted values is important in optimization of tunneling activities. This includes the analysis of rate of penetration and machine utilization factor as the main focus of such studies. This paper offers an overview of TBM performance in Lot 1 and 2 of Karaj water conveyance tunnel project for a length of 30 km located in northwest of Tehran. Study of monthly utilization and rate of penetration for both tunnels shows that AR fluctuates are more susceptible to U than ROP. Statistical analysis of the data indicates that activities such as Maintenance, TBM Breakdowns, shift changes, segment installation are more influential than surveying and re-gripping in determining machine utilization. Therefore to optimize AR and U one can focus on the critical items.

1 INTRODUCTION

Performance analysis of Tunnel Boring Machine (TBM) and development of accurate model for prediction of machine performance is one of the main targets for many ongoing studies. TBM performance refers to rate of penetration (ROP), utilization factor (U) and advance rate (AR). Utilization factor is defined as the percentage of boring time to total time.

In recent years, along with the advancement machine features and capabilities, especially in computerized monitoring and control of various machine functions, the machines have become very powerful and somewhat smart machines. Machine productivity has constantly increased and new records have been achieved in past few years. But it is still difficult to accurately estimate TBM utilization under variety of rock mass conditions due to operational and geological uncertainties. Evaluation of TBM performance during construction of a tunnel is an important issue in mechanized tunneling.

Several TBM performance predicting models have been developed through the years since the accurate estimate of machine penetration and advance rate is the key issue in scheduling and cost estimation for a given tunneling project. Most of these models have been developed only for estimating rate of penetration. Only few models such as CSM, NTNU and Q_{TBM} offer formulas for calculating utilization factor. Kim (2004) developed a utilization predictor model based on fuzzy logic. Some attempts also have been made to correlate rock mass classification systems, TBM advance rate, utilization factor and TBM rock mass related down times using statistical and RES approaches (Frough et al. 2012 and 2013).

It must be noted that despite the importance of utilization, limited amount of research has been focused on this topic due to lack of data and complexity of the influencing parameters. In this paper, performance parameters in 2 long mechanized tunnels (Karaj 1 and 2) are analyzed and role of utilization factor in advance rate will be examined. This study will also look at the main parameters with highest impact on the machine utilization which can be subsequently modified to increase machine productivity and advance rate.

2 INFLUENTIAL PARAMETERS ON UTILIZATION FACTOR

The main causes for lower utilization and loss of boring time vary significantly from site to site. Generally speaking; TBM downtimes include the times for support installation, re-gripping, grouting, maintenance, machine break down, cutter change, mucking delays, stoppage caused by geological adverse conditions and other components such as shift changes and breaks (Rostami and Ozdemir, 1993, Bruland 1998, Farrokh et al. 2012). During the excavation process, various factors including machine parameters, geological conditions and site facilities, affect TBM utilization level (Kim, 2006). Previous studies show that geological adverse conditions have a great impact on TBM downtimes. Instability and collapses cause long downtime due to the necessity for ground improvement and cleaning of rock falls in the tunnel or face collapse. Similarly groundwater can negatively affect utilization and cause substantial delays in tunnel boring operations. Estimation of the utilization factor as a function of machine specifications and rock mass properties can be the most critical parameter to compute the advance rate, yet there are limited work and models for this purpose.

Main activities that have major effect on TBM utilization and ROP are summarized in Table 1. According to this table main activity of TBM is boring. Others are support activities or forced stoppages that are cause of TBM downtimes are classified in 7 groups in current study. This primarily based on the available data and recorded field parameters. Although activities in these groups occur mostly in series with boring cycle, most of these activities can easily be performed at the same time or in parallel. For example during TBM stoppage in weak rock masses prone to frequent rock falls, some maintenance or cutterhead inspection or utility installation can be performed parallel to ground support installation to avoid additional stoppage of TBM.

3 KARAJ WATER CONVEYANCE TUNNELS

In order to evaluate TBM performance and impact of variable parameters on machine utilization, various activities and downtime components, Karaj-Tehran water conveyance tunnel were studied in detail. This tunnel were recently completed for a total length of 30 km in two sections, lot-1 16 km, and lot-2 13.6 km, with an excavated diameter of 4.66 and finished diameter of 3.9 m. The tunnels are located in northwest of Tehran and were designed for transferring 16 m^3/s of water from Amir-Kabir dam to Tehran. Location of the tunnel is shown in figure 1.

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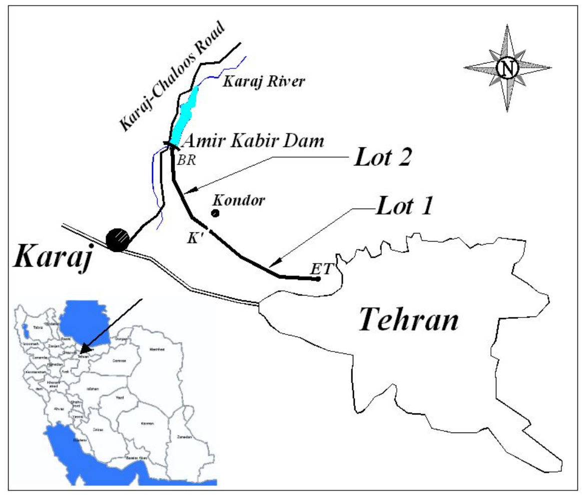

Figure 1.Location of the Karaj-Tehran water conveyance tunnels

The first 140 m of the lot 1 were excavated by conventional methods (Roadheader). The double shield TBM manufactured by Herrenknecht AG were assembled at the portal and pulled to the face. The maximum overburden in Lot-1 was 670 m, with an average of about 400 m. In the second lot, the first 133 m starter tunnel was excavated by conventional methods (drilling and blasting) and then TBM was used to finish the tunnel. The maximum overburden in Lot 2 was 820 m, with an average depth of about 350.

The first Lot were excavated and lined by the TBM and then machine were refurbished and in a portal area between the two tunnels and used for excavation and lining of Lot 2 (Figure 2). Specifications of utilized TBM are listed in Table 2. The tunnels were lined with 5 + key pre-cast concrete segments in tetragonal arrangement and thickness of 25 cm.

Table 1- Activities having major effect on TBM utilization

No	Activities or Downtimes	Description	Situation	Influence	duration
1	Boring			ROP	Main activity
2	Re-gripping		S*	U	After each boring cycle
3	Ground support	Support installation	P*/S	U	After each boring cycle
		Cutter head cleaning	S	U	if clogging occurs
		Clear rock fall	S	U	If collapse occurs
		TBM releasing	S	U	If a large collapse or squeezing occurs
		Ground improvement	S	U	if there is a weak rock
		Dewatering	S/P	U	if water flow occur
		Probe drilling	S	U	if there is a weak rock
		Delay because of Poisonous gas	S	U	if gas exists
		Extra cutter changing	S	U/ROP	if there is an Abrasive rock
4	Maintenance	Washing	S	U	every shift
		Cutter inspections	S	U/ROP	every shift
		Routine cutter change	S	U/ROP	If necessary
		Routine maintenance	S	U	every shift (Electrical, Mechanical, Hydraulically: TBM and Back up)
5	Utility instalation	Water pipe	S	U	due to length of pipes (every 50m)
		Power cable	S	U	due to length of flexible cable (every150 to 250m)
		Ventilation duct	S	U	due to length of duct (every100 to 250m)
6	Transport	Rail extension	P/S	U	due to length of rails (every 6 to 12m)
		Train delay	S	U	
		Unloading problems	S	U	sometimes depend on rock mass condition
7	Surveying	Changing stations	S	U	due to tunnel aliment (straight: every 250m, curves: every 50m)
8	Unexpected breakdowns	Elec., Mech., Hydraulic.	S	U	unexpected
		Conveyor belt maintenance	S	U	unexpected (sometimes depend on rock mass condition)
		Delays for supply or spare parts	S	U	unexpected (sometimes depend on management)
9	Other delays	Lunch time	S	U	every shift (depend on management)
		Shift change	S	U	every shift (depend on management)
		Others	S	U	unexpected

*S: Series to Boring, *P: Parallel with Boring

Figure 2- TBM utilized in these tunnels, Left) after first assembly in Karaj 1, Right) overhaul before application in Lot 2

Table 2.Specifications of utilized TBM

Specification	Karaj tunnels
Machine diameter (m)	4.66
Cutters diameter (mm)	432
Cutter disk spacing (mm)	70
Number of cutters	31
Cutter head power (KW)	1250
Cutter head speed (RPM)	11
Cutter head torque (kN-m)	2500
Max cutter head thrust (kN)	17,000

4 SITE GEOLOGY

The lithology of karaj tunnel lot 1 and 2 area consists of a sequence of Karaj formations. In lot 1 the lithology is composed of variety of 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 (SCE 2004). In this tunnel, main adverse geological conditions consist of existing clay, raveling in crushed zones, falling rock wedges and some water problems. The lithology of lot 2 contain of variety of pyroclastic rocks, often interbedded with sedimentary rocks. The characteristic rock type in this section is gray tuff, siltstone, sandstone, monzodiorite and monzogabro (SCE 2009). In this lot, groundwater problems were the main adverse geological condition.

5 EVALUATION OF TBM PERFORMANCE

In order to evaluate the effect of various ground conditions and operational issues on TBM performance (ROP and U), field data from Lot 1 and 2 of Karaj tunnel were examined in detail. The collected data consist of the boring times, downtimes, geological features and operational parameters. Table 3 contains performance parameters in the two sections of the Karaj tunnel. Figures 3 and 4 show the plots of AR versus ROP and U. The purpose is to evaluate the variability of the two main parameters impacting daily advance and their range of fluctuations. As it can be seen in both tunnels, the AR fluctuates more with U than ROP. This means that in this project, ROP was more or less constant (limited variations) and most of the changes in AR was due to variations in the distribution of downtime and utilization.

Descriptive statistical analysis of available data from the two Lots of Karaj tunnels is summarized in Table 4. Figure 5 and 6 shows the AR plots versus ROP and U in both tunnels. It is evident from these figures that AR has meaningful and significant relationship with U rather than ROP.

Naturally, any increasing in U can increase AR. Given the fact, many of the tunnel activities can be carried out in parallel and some of them even parallel to boring cycle, a good site management and precise scheduling with minor extra cost can increase U and naturally AR. However, range of variations in ROP is more restricted and its increase does not map directly to increase in daily advance.

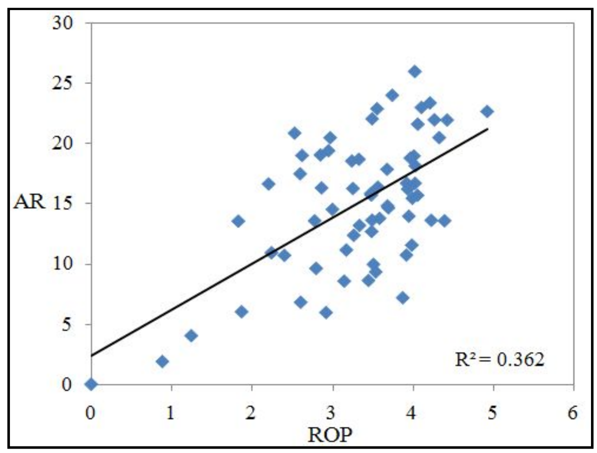

Figure 5.Variations of AR according to ROP

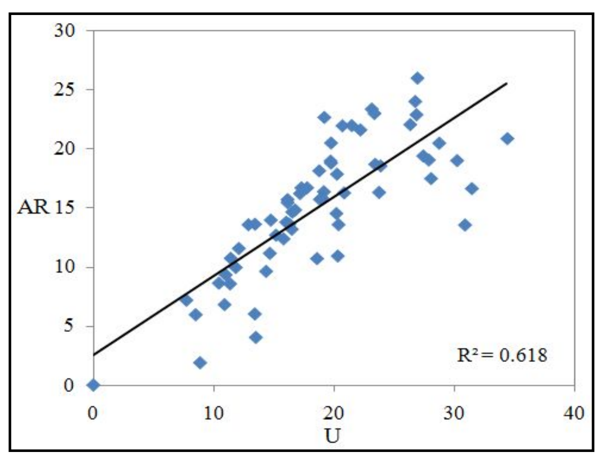

Figure 6.Variations of AR according to U

Table 3.Performance parameters of Karaj 1 and 2

Parameters		Karaj 1		Karaj 2	
		daily	Monthly	daily	Monthly
penetration rate (m/h)	Maximum	7.3	4.93	6.63	4.43
	Average	3.32	3.59	2.72	3.03
Utilization factor (%)	Maximum	53.8	26.88	52.01	34.33
	Average	17.62	17.54	20.29	20.27
Advance rate (m/d)	Maximum	38.9	25.96	39.03	22.97
	Average	15.4	15.33	14.93	14.81

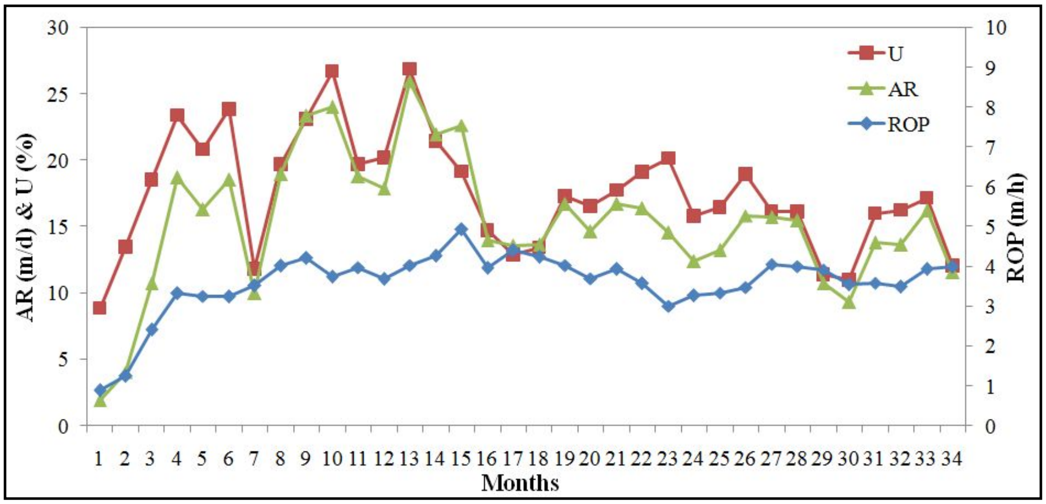

Figure 3.Variations of AR in comparison of ROP and U in Karaj 1

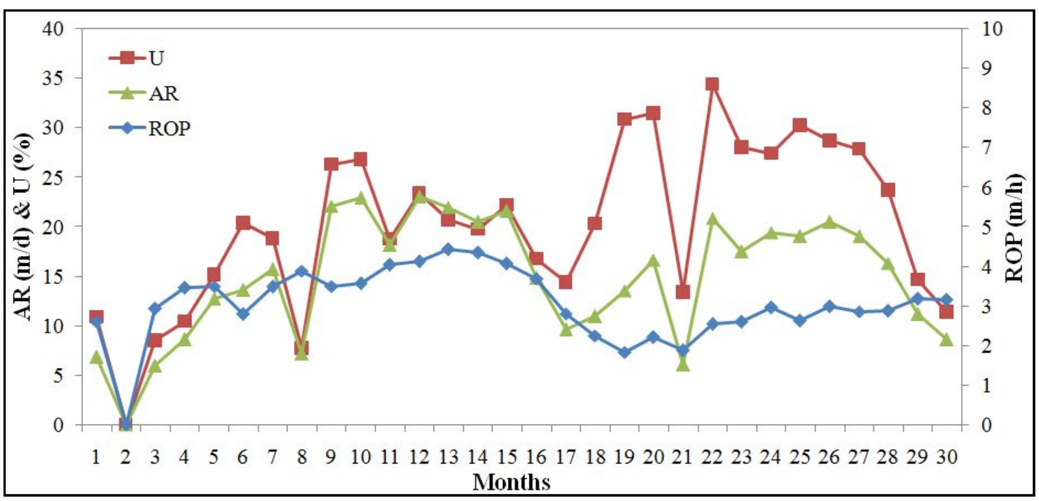

Figure 4.Variations of AR in comparison of ROP and U in Karaj 2

Table 4.Descriptive statistics of data

Parameters	ROP (m/h)	AR (m/d)	U (%)
Mean	3.33	15.08	18.73
Std. Error of Mean	0.113	0.70	0.82
Std. Deviation	0.883	5.59	6.58
Variance	0.78	31.30	43.36

List of different tunneling activities is offered in table 1. Some of these activities have more influence on U than others. To develop a more realistic understanding of time distribution between these activities, components of machine downtime were normalized in hours per unit length of tunnel Average time distribution for these activities. According to Figure 7 the main influencing downtime components were Maintenance and Breakdowns, Segment Installation and Shift Changes in both tunnels. In Lot 1 GRRD has considerable effect on utilization because of ground problems, and in Lot 2 Transporting delays affected utilization due to longer distance for segment haulage through Lot 1 tunnel requiring a round trip of over 16 kilo meters.

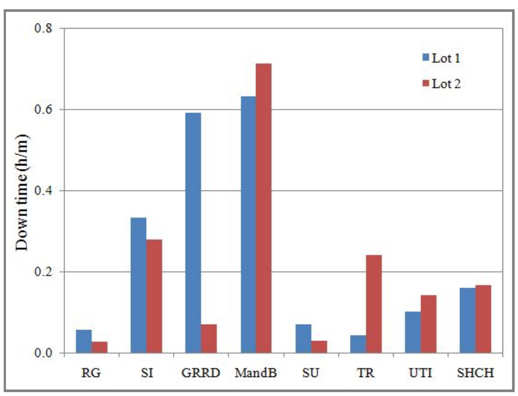

Figure 7.Average different downtimes (h/m)

Parameters in Figure 7 include U=Utilization factor, RG=Re-gripping, SI=Segment Installation, GRRD=Geological and Rock mass Related Downtimes, MandB=Maintenance and Breakdowns, SU=Surveying, TR=Transporting, UTI=Utility installation and SHCH=Shift Change and other downtimes. For evaluation of relationship and influence of each activity on utilization, Pearson correlation coefficient has been used. Pearson coefficient is only sensitive to a linear relationship between two variables. This coefficient indicates the strength of a linear relationship between two variables, but its value generally does not completely characterize their relationship. Rank of the Pearson correlation coefficients measure the extent to which, one variable affects the other variables. If increases in one variable leads to decrease in other variable, the rank correlation coefficients will be negative. In this study the statistical package SPSS 15 (2006) were used for conducting the required analysis. Table 5 summarizes the estimated Pearson correlation and related rank between different variables in this project. According to this table, MandB, SHCH and SI are more influential on Utilization but the correlation coefficients are negative. On the other hand, SU and RG have no meaningful linear relation with U, which could mean possibly a nonlinear relation between these parameters.

Table 5.Rank correlation coefficients measure with U

Parameter	Pearson Correlation	Sig. (2-tailed)
MandB	-0.563	0.000
SHCH	-0.467	0.000
SI	-0.309	0.014
GRRD	-0.295	0.019
UTI	-0.284	0.024
TR	-0.257	0.042
SU	-0.149	0.245
RG	-0.132	0.302

Obviously the relationship between U and the delay components are simply defined as:

$$U = \frac{\text{Boring Time}}{(\text{Boring} + \text{Rg} + \text{SI} + ...)}$$

However various linear regression analysis techniques were used to develop an understanding of the impact of various delay components on utilization. In this statistical analysis, downtime values for each category were considered as independent input variables whereas the measured U were taken as objective variable. An equation consisting of all downtimes and another with maximum Adjusted R Square are offered below. While these equations are not useful in predicting utilization for an upcoming project, they can assist in illustrating the degree of variability of various delay components and the components that have the highest impact on the utilization. As can be seen in Equation 2, the downtime components with highest impact on the utilization are maintenance, Misc and shift change, utility installation, and segment installation. This indicates that the other components, although substantial portion of the downtimes, they are less variable and it is likely that these downtime components are streamlined.

U = 29.94 – 2.05 RG – 13.28 SI – 1.05 GRRD – 4.23 MandB + 7.36 SU + 2.33 TR – 19.53 UTI – 11.69 SHCH (Eq n. 1)

U = 30.45 – 15.31 SI – 4.32 MandB – 14.74 UTI – 12.62 SHCH (Eq n. 2)

Table 6.Models Summary

Model	R	R Square	Adjusted R Square	F	Sig.
1	0.68	0.47	0.39	5.90	0.00
2	0.68	0.46	0.42	12.12	0.00

More in depth analysis of the data is underway to find the range of variability of the down time components and their relationship with various geological and operational parameters. This would allow for developing equations for prediction of the utilization based on operational activities and related delay times for a given tunneling project with certain type machine and given ground conditions. The same analysis can also assist in optimization of the operation and maximizing U an AR

6 CONCLUSIONS

TBM advance rate is a function of rate of penetration and utilization factor. ROP is limited by machine specifications and rock mass parameter and range of variations in ROP is more restricted. U is controlled by more parameters such as geology and rock mass characteristics, maintenance, utility installation, transportation, surveying and unexpected breakdowns. Many of tunnel activities can be carried out in parallel. Finding the way to increase boring time means increasing utilization factor since it can influence the AR more than ROP.

The influences of different downtimes on TBM utilization factor were examined using regression analysis. For evaluation of relation and each activities influence on U, Pearson correlation coefficient has been applied and it is found that MandB, SHCH and SI are more influential components of downtime when it comes to controlling utilization in the case of the Karaj Water tunnel used in this study. SU and RG showed no meaningful relation with U, thus less important in improving machine utilization.

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