

Evaluation of boring machine performance with special reference to geomechanical characteristics

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Abstract: The duration of tunneling projects mostly depends on the performance of boring machines. The performance of boring machines is a function of advance rate, which depends on the machine characterizations and geomechanical properties of rock mass. There were various theoretical and empirical models for estimating the advance rate. In this paper, after determining the geomechanical properties of rock mass encountered in the Isfahan metro tunnel, the performance of the roadheader and tunnel boring machine (TBM) were then evaluated using various models. The calculation results show that the average instantaneous cutting rate of the roadheader in sandstone and shale are 42.8 and 74.5 m³/h respectively. However the actual values in practice are 34.2 and 51.3 m³/h. The operational cutting rate of the roadheader in sandstone and shale are 8.2 and 9.7 m³/h respectively, but the actual values are 6.5 and 6.7 m³/h. The penetration rate of the TBM in shale is predicted to be 50-60 mm/round.

Key words: performance prediction; roadheader; cutting rate; specific energy; tunnel boring machine; penetration rate

1. Introduction

Underground areas in the form of tunnels and caves have always been intended by man from the very beginning of his advent as a place for storing food stuff, sheltering or hiding. In early times, tunnels were dug using primitive hand made tools. Upon the discovery of dynamite by Noble, tunnel excavation was changed to a new form, and blasting rapidly superseded manual and traditional methods. In the course of time, however, it was clear that blasting excavation could not suffice in long tunnels due to low speed and high risks. Mechanized tunnel excavation is especially important relative to blasting due to high speed and low costs and sound pollution in long tunnels.

The study of the performance of mechanized excavators was based on the geomechanical properties. Hence, the instantaneous cutting rate (ICR) estimation models were utilized. By determining the ICR and utility coefficient, the operational cutting rate (OCR) was computable. Hence, the machine performance was evaluated.

In this paper, by using the cutting rate estimation models and comparing relevant results with what has been obtained in practice, the operation of roadheader

and tunnel boring machines (TBM) employed in Isfahan metro tunnel project, the north-south route was assessed.

2. Model descriptions

2.1. Roadheader cutting rate estimation models

There are various models for predicting the roadheader cutting rate. These are as follows.

(1) Model of Copur *et al.* They used the data collected from a roadheader at Colorado School of Mine and derived the following equations [1]:

$$ICR = 27.511 \times e^{0.0023RPI}$$

$$RPI = PW/UCS$$

(2) Model of Bilgin *et al.* Using core cutting test results of roadheaders, the following predictive equation was derived [2-3]:

$$RMCI = UCS(RQD/100)^{2/3}$$

$$OCR = 28.06 \times 0.997^{RMCI}$$

$$ICR = 0.28P \times 0.974^{RMCI}$$

(3) Model of McFeat-Smith. The derived equation is based on specific energy test results from roadhead-

ers [4]:

$$SE = -4.38 + 0.14(0.0377UCS + 0.254)^2 + 3.30UCS^{\frac{1}{3}} + 0.000018(0.441UCS - 8.37)^3 + 0.0057CC^3,$$

$$ICR = \eta \frac{HP}{SE}.$$

(4) Model of Sandbak. Sandbak demonstrated a linear correlation between the performance (operational cutting rate and bit consumption) and Bieniawski's rock mass rating (RMR) [4].

(5) Model of Fowell *et al.* This model is based on results obtained from simulation of excavating machines in the laboratory [5].

$$ICR = 0.6SA \cdot AR \cdot RPM$$

(6) Model of Rostami *et al.* It is one of the most accepted methods to predict the cutting rate of any excavating machine using the cutting power, specific energy obtained from full scale cutting tests and energy transfer ratio from the cutting head to the rock formation as the following equations [3, 6-7]:

$$ICR = k \frac{P}{SE_{opt}},$$

$$SE_{opt} = 0.027UCS \cdot BTS + 0.675.$$

where RPI is the roadheader penetration index; P the cutterhead power, kW; W the roadheader weight, t; UCS the uniaxial compressive strength, MPa; RMCi the rock mass cuttability index; RQD the rock quality drilling, %; SE the specific energy; CC the cementation coefficient; HP the horse power; η the efficiency; SA the swept area, m²; AR the cutter head advance, cm; RPM the rate per minute; SE_{opt} the optimum specific energy, kW·h/m³; k is the energy transfer coefficient depending on the mechanical miner utilized, and it changes between 0.45 and 0.55 for roadheaders and from 0.85 to 0.90 for TBM; and BTS the brazilian test strength, MPa.

2.2. TBM cutting rate estimation models

(1) The NTH (Norwegian Institute of Technology) model. In this model, the TBM penetration rate (PR) is calculated by determining Sievers's J index (S_j), abrasion testing (AV), brittleness test (S_{20}), drilling rate index (DRI), cutter life index (CLI), bits wear index (BWI) and correction factor (k) which is found from joint classes [8-10].

(2) The CSM (Colorado School of Mines) model. The PR is calculated based on determining the vector of the forces applied from the cutters to the rock. These forces are a function of cutter radius (R), cutter

tip width or thickness (T), space between cutters (S), rock uniaxial compressive strength (σ_c) and rock tensile strength (σ_t) [8].

(3) The RSR (rock structure rating) model. The penetration rate is as follows [11]:

$$PR = 40.41UCS^{-0.44} + 0.047RSR + 3.15,$$

where RSR is the classification system rating.

(4) The Q_{TBM} model. This model is presented based on the rock mass classification system (Q), average shear force, rock abrasiveness and stress level [12].

$$Q_{TBM} = \frac{RQD_0}{J_n} \cdot \frac{J_r}{J_a} \cdot \frac{J_w}{SRF} \cdot \frac{UCS}{F^{10}/20^9} \cdot \frac{20}{CLI} \cdot \frac{q}{20} \cdot \frac{\sigma_0}{5}.$$

Barton derived a simple relationship between penetration rate and Q_{TBM} :

$$PR = 5(Q_{TBM})^{-0.2},$$

where RQD₀ is the conventional RQD interpreted in the tunneling direction, J_n the joint number, J_w the joint water reduction, J_r the joint roughness, and J_a the joint alteration. J_n , J_w , SFR, J_r , and J_a are unchanged from conventional Q . F is the average cutter load, kN; CLI the cutter life index; q the quartz content, %; and σ_0 the induced biaxial stress on tunnel face, MPa [12].

3. Isfahan metro project specifications

Isfahan metro network is 123 km long and at present, only small part of the route, *i.e.*, the north-south branch, 12 km long is being excavated. This branch includes 3 parts. The south line, 4 km in length, is excavated with the roadheader; the middle line, 5.5 km in length, is excavated with the TBM; and the north line, 2.5 km in length, is excavated with cut and fill methods. Fig. 1 shows the north-south branch of the Isfahan metro tunnel.

The roadheader used is a WIRTH model T2.11 type [14]. Its main characteristics are as follows: diameter 0.8 m, power 460 kW, weight 75 t, and revolution rate 65 r/min.

The TBM used is a Herrenknecht model [15]. Its main characteristics are as follows: diameter 6.89 m, cutter wheels (number and size) 6 and 416 mm, installed power 945 kW, revolution rate 2.5 r/min, and torque 3500 kN·m.

To calculate utility coefficient (U) (drilling time / shift time), time measurement was performed during one drilling shift. Table 1 show the operation performance time in each step of progress for sandstone and shale.

Based on measured time and daily site report, the roadheader efficiencies in sandstone and shale were determined to be 90% and 75% respectively.

The south line tunnel with an arch shape having a cross-sectional area of 38.5 m², passes mainly through shale and sandstone rocks, which contains 20%-40% quartz. Fig. 2 shows the geotechnical longitudinal section of the south line tunnel.

Generally, the middle line consists of alluvium (except for a distance of 1000 m between Shariati station and Azadi). Fig. 3 shows the middle line section.

UCS and BTS tests were conducted in the laboratory in accordance to ISRM suggested methods [16] as shown in Table 2. The RMR, *Q* and RSR [17] values for sandstone and shale were then determined.

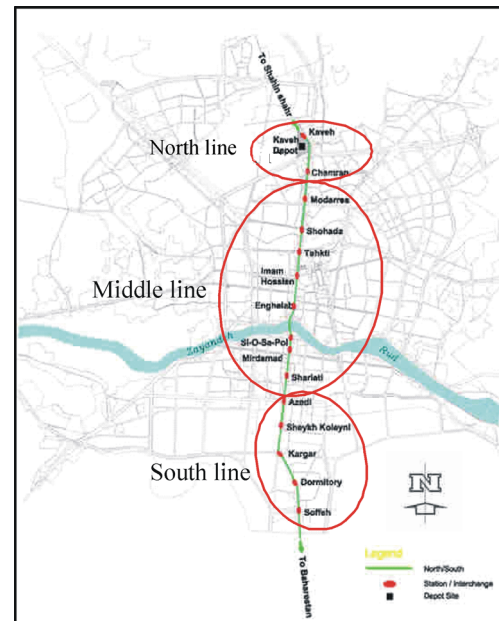


Fig. 1. North-south branch of the Isfahan metro tunnel.

Table 1. Time distribution in roadheader excavation for the south line

In each step of progress	Sandstone		Shale	
	Time distribution / h	Proportion / %	Time distribution / h	Proportion / %
Excavation	2.5	21	2	17
1st layer shotcreting	1.5	13	1.5	13
1st row mesh installation	0.75	6	0.75	6
Latic installation and welding	2	17	2.5	21
2nd row mesh installation	0.75	6	0.75	6
2nd layer shotcreting	1.5	13	1.5	13
Cleaning	1	8	1	8
Equipment installation	1	8	1	8
Breakfast/lunch/dinner/break	1	8	1	8
Total	12	100	12	8

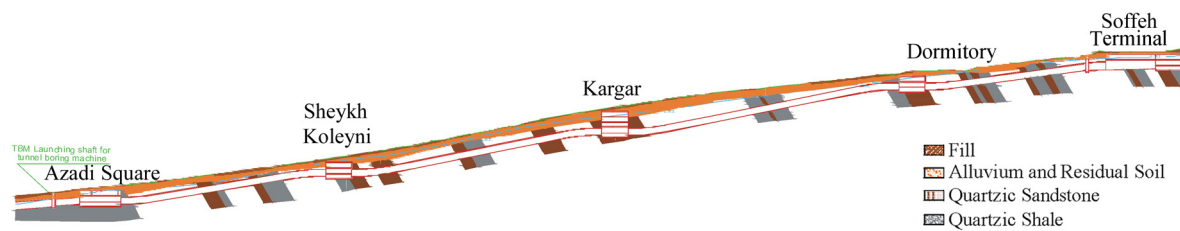


Fig. 2. South line section.

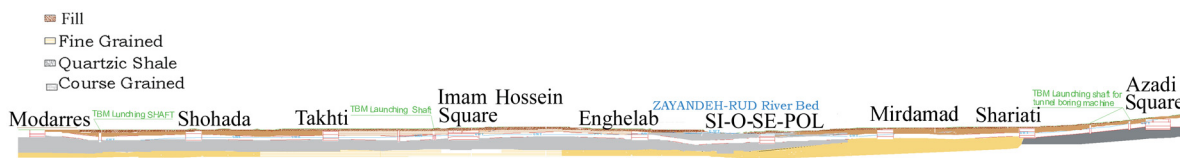


Fig. 3. Middle line section.

Table 2. Isfahan metro tunnel geomechanical parameters

Rock type	Classification system			Geomechanical parameters		
	RSR	RMR	<i>Q</i>	RQD / %	BTS / MPa	UCS / MPa
Sandstone	52	37	0.33	40	4.13	49
Shale	39	25	0.036	20	3.48	17.5

4. Calculation results

4.1. OCR and ICR of roadheaders

Table 3 shows the results obtained from applying rock parameters and roadheader specifications in the OCR/ICR determination models. For calculating the

OCR, the utility coefficient (U) should be obtained. According to Table 1 and the machine efficiency, the U value was calculated to be 0.19 and 0.13 for sandstone and shale respectively. The OCR is calculated by the following equation: $OCR = ICR \times U$.

Table 3. OCR and ICR values obtained from the models

Models	OCR / ($\text{m}^3 \cdot \text{h}^{-1}$)		ICR / ($\text{m}^3 \cdot \text{h}^{-1}$)	
	Shale	Sandstone	Shale	Sandstone
Copur <i>et al.</i>	333.2	26.4	2562.7	138.9
Bilgin <i>et al.</i>	27.6	25.9	145.5	85.2
McFeat-Smith	12.5	9.3	85.9	44.7
Fowell <i>et al.</i>	9.1	8.9	70.5	46.8
Sandbak	7.2	8.1	55.0	42.7
Rostami <i>et al.</i>	12.9	7.2	99.1	37.5

Although the model of Copur *et al.* was developed for evaporate rocks without joints and cracks, they stated that their model can also be used for other rock types. However, it is observed that the results obtained from this model were much different from the values from other models and the mean values. Hence, this value was omitted from the analysis. Figs. 4 and 5 show a comparison between the actual and estimated model values of ICR and OCR respectively.

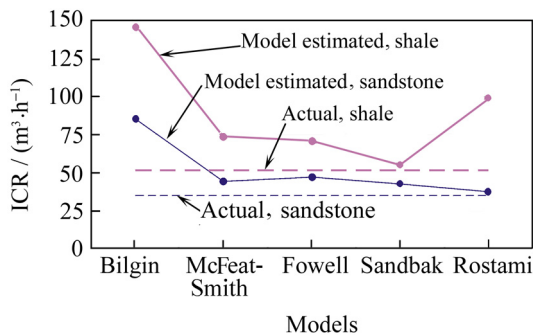


Fig. 4. Actual and estimated model values of ICR.

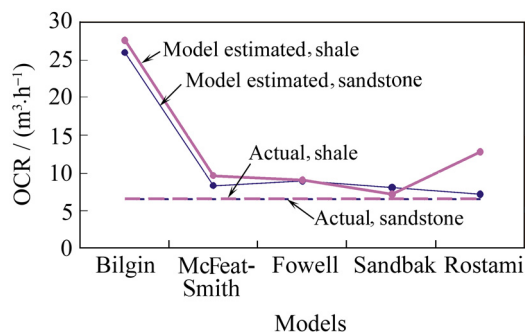


Fig. 5. Actual and estimated model values of OCR.

As shown in Fig. 4, the ICR obtained from the model of Bilgin *et al.* is significantly different from other models. Thus, the model of Bilgin *et al.* does not seem appropriate for assessing the roadheader operation in sandstone and shale layers in the south line. It is noteworthy that the trend of difference in OCR ob-

tained from the model of Bilgin *et al.* (Fig. 5) is also observable.

Regarding the ICR/OCR values obtained from the Sandbak model in comparison with the actual values in practice, the model seems appropriate to assess the roadheader performance in shale formation which exists in the Isfahan metro tunnel south line.

As shown in Fig. 4, there are generally differences between the ICR values calculated from different models. The calculated values exceed those obtained from the actual performance.

On the other hand, since the roadheader technical specifications used to calculate the ICR values exceed the real ones in all models, the T2.11 roadheader for excavating sandstone and shale in the south line did not seem to be an optimal and appropriate choice.

From Fig. 5, it is observed that the practically obtained OCR values for shale and sandstone are generally close to each other.

To compare the estimated and actual values of ICR and OCR, the mean ICR and OCR of appropriate models are utilized as shown in Table 4.

Table 4. Comparison between the actual and calculated OCR and ICR

Rock type	OCR / ($\text{m}^3 \cdot \text{h}^{-1}$)		ICR / ($\text{m}^3 \cdot \text{h}^{-1}$)	
	Actual	Calculation	Actual	Calculation
Sandstone	6.5	8.2	34.2	42.8
Shale	6.7	9.7	51.3	74.5

4.2. TBM penetration rate

The penetration rate of the TBM was predicted using the models described above. Table 5 shows a summary of results obtained from the PR models.

Table 5. TBM penetration rate prediction

Models	PR for shale / (mm/round)
CSM	59
RSR	16.1
Q_{TBM}	49.4

It should be noted that In Isfahan metro twine tunnel project, 2 TBM machines started excavating where the ground material is mainly alluvium but not shale.

However from site reports the TBM penetration rate (PR) in alluvium is 50-65 mm/round at present which confirm the values obtained from the 2 models of CSM and Q_{TBM} .

Mean while, the PR value obtained from the RSR model does not seem to be appropriate for determining the PR in shale for the middle line.

5. Conclusion

The results obtained show that among the models used in this paper, the models of Rostami *et al.* and McFeat-Smith seem more suitable for assessing the roadheader performance in the sandstone formation of the Isfahan metro tunnel south line, whereas the models of Copur *et al.* and Bilgin *et al.* seem inappropriate. It is also found that models which are based on specific energy seem to show closer results to reality.

Among the models used to assess the roadheader performance in shale, the Sandback model seems more appropriate and the models of Copur *et al.* and Bilgin *et al.* seem inappropriate.

Generally, the ICR real value is less than those obtained from the models, and since the models results confirm each other well, the roadheader does not seem to have been an optimal choice.

The ICR in shale is much more than that of sandstone.

The TBM penetration rate in shale layers is predicted to be 50-60 mm/round.

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