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A new model to predict roadheader performance using rock mass properties

Yazdani-Chamzini ABDOLREZA[1], SIAMAK Haji Yakhchali[2]

1. Young Researchers Club, South Tehran Branch, Islamic Azad University, Tehran 14115/344, Iran

2. Department of Industrial Engineering, College of Engineering, University of Tehran, Tehran 11365/7117, Iran

Abstract Prediction of roadheader performance plays a significant role in the plan of tunnel construction, which is influenced by different key parameters, including rock strength, discontinuity in rock mass, type and specifications of roadheader machine, and brittleness. The main aim of this study is to build a robust empirical equation based on rock mass properties for the roadheader performance prediction. For achieving the aim, a dataset composed of roadheader performance rate and rock properties is established using the dataset compiled from an underground coal mine located in a remote rugged desert environment some 85 km south of Tabas City in mid east Iran. By using gathered data, the statistical analyses are conducted between rock mass properties and roadheader performance to find whether there is a significant relationship between input variables and roadheader performance. The results show that rock mass properties have a considerable impact on the rate of the roadheader performance. It is demonstrated that the proposed model can accurately predict the roadheader performance as a function of rock mass properties.

Keywords roadheader performance, Tabas Coal Mine, rock mass property, alpha angle, prediction

Introduction

Roadheader, one of the most common mechanized methods in tunnel construction, has been widely used for excavating tunnels and developing mines in soft to medium strength rock conditions. This machine is favored in tunneling and mining operations because of its unique features, including its ability to excavate almost any profile opening, low capital costs, a high degree of mobility, flexible cutting profile (i.e., horseshoe), selective mining, providing immediate access to the face and the capability to cut medium rocks with a compressive strength of up to about 100 MPa (Copur et al., 1998; Ebrahimabadi et al., 2011a).

The performance analysis of roadheader machines plays a significant role in tunnel completion time and cost; so that, accurate prediction of the roadheader performance has a key impact on the successful planning of the tunneling project. According to the importance of the problem, several researches are conducted to find a significant relationship between the roadheader performance and other parameters influencing the performance of the machine (Bilgin et al., 1988, 1990, 2006; Gehring, 1989; Fowell and Johnson, 1991; Rostami and Ozdemir, 1996; Copur et al., 1998; Thuro and Plinninger, 1999; Goshtasbi et al., 2009; Ebrahimabadi et al., 2011a, 2011b). In order to predict the roadheader performance, the estimation of instantaneous cutting rate (ICR), the production rate during actual cutting time (m^3/h), is required.

Different input parameters are employed to model the rate of the roadheader performance. Uniaxial compressive strength (UCS) is one of the most popular input parameters for predicting the roadheader performance on account of its simple assessment (Uehigashi et al., 1987; Schneider, 1988; Gehring, 1989; Thuro and Plinninger, 1999; Tumac et al., 2007; Madan, 2008).

A rock classification system was applied by Sandbak (1985) and Douglas (1985) to explain the changes of roadheader advance rates at San Manuel Copper Mine in an inclined drift at an 11% grade. A roadheader performance model based on UCS and rock quality designation (RQD) is developed by Bilgin et al. (1988, 1990). Copur et al. (1998) used the data collected from a roadheader at Colorado School of Mine to predict the roadheader performance based on three

Accepted: 25 November 2012
E-mail: abdalrezaych@gmail.com, yakhchali@yahoo.com

factors, the roadheader penetration index, the cutter-head power, and the roadheader weight.

Fowell and Johnson (1991) developed a model based on results obtained from simulation of excavating machines in the laboratory, in which three parameters of the swept area, the cutter head advance, and the rate per minute are applied to model the rate of the roadheader performance. Poole (1987), Farmer and Garrity (1987) and Keleş (2005) developed one of the simplest prediction methods that was formulated based on specific energy values to predict the excavation rate for a given power of roadheader.

One of the most accepted methods to predict the cutting rate of any excavating machine is to use cutting power, specific energy obtained from full scale cutting tests and energy transfer ratio from the cutting head to the rock formation (Rostami & Ozdemir, 1996; Balci et al., 2004; Bilgin et al., 2004). Other researchers have gone one step further and proposed a model to predict the performance of roadheaders based on the rock mass brittleness index (Ebrahimabadi et al., 2011a). Ebrahimabadi et al. (2011b) investigated the influence of alpha angle (the angle between tunnel axis and the planes of weakness) on roadheader performance and found a high correlation between *ICR* and alpha angle (α).

Various studies have been accomplished for predicting the roadheader performance mostly based on rock mass properties that are not reliable and accurate enough to model the rate of the roadheader performance. On the other hand, many of the above-mentioned researches have only taken into account one parameter as independent variable and the models constructed are often univariate; whereas, the role of other effective variables has simply been ignored. Consequently, attempts should be carried out to modify the existing models or propose new models that consider effective independent variables on the rate of roadheader performance.

1 Project description

Tabas Coal Mine locates in a remote rugged desert environment some 85 km south of Tabas City in mid east Iran. This mine is the largest semi-mechanized coal mine in Iran. The mine is divided into three parts Parvadeh, Nayband and Mezino areas as shown in Fig.1. Parvadeh underground coal mine (Tabas No.1 coal mine) region with the extent of 1 200 km^2, 1.1 billion tones of estimated coal reserve and dig angle of 29.5° is the biggest and main part to continue excavation and fulfillment for future years (Ebrahimabadi et al., 2011b; Lashgari et al., 2011). Fig.2 shows Parvadeh mine and other districts of the coal region of Tabas. Production rate of this mine is about 4 000 t of coal per day, because of the suitable geometry of the coal seams and large extent of the deposit, mechanized excavation methods are applied in the mine. The coal thickness varies from 0.5 to 2.2 m with a reduction trend in thickness from west to east. The coal seam has a consistent 1.8 m thickness in the majority. Two extraction methods of long-wall, and room-and-pillar are applied for mining in this mine. Coal mining by the long-wall method with powered roof supports requires rapid advance of the access roads (Ebrahimabadi et al., 2011a). This increases the demand for roadheader, one of the most popular excavation methods, due to unique features in excavating coal seams, especially when the method of extraction is room and pillar. Likewise, the two alternatives for mining very thick coal seams, i.e. room-and-pillar and long wall in fat seams, require the use of roadheader driving galleries in the coal seams (Ebrahimabadi et al., 2011b). The basic specifications of the roadheader are shown in Table 1.

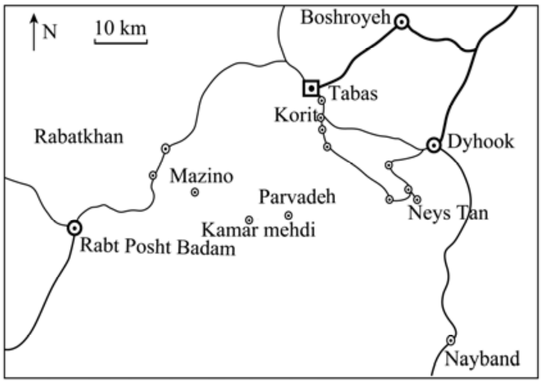

Fig.1 Three areas in Tabas coal region (Asadi et al., 2005)

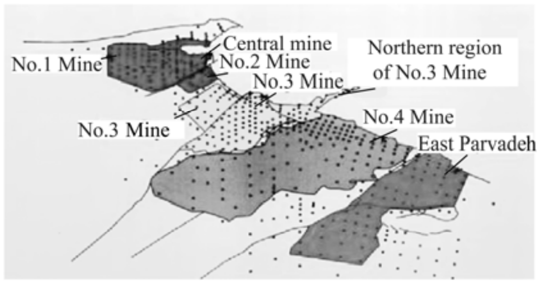

Fig.2 Districts of the coal region of Tabas (Lashgari et al., 2011)

Table 1 Specifications of the of DOSCO MD 1100 roadheaders

Items	Specification
Machine weight	34 tons
Total power	157 kW
Power on cutting boom	82 kW axial, 112 kW transverse
Hydraulic system working pressure	140 bar
Tracking speeds-Sumping/Flitting	0.038/0.12 m/s
Ground pressure	1.4 kg/cm²
Machine length	8 060 mm
Machine width	3 000 mm
Machine height	1 700 mm

2 Database

The database on roadheader performance comprises different levels of information, which describes rock mass conditions and situation of discontinuities. The database contains data on Tabas coal mine project and comprises 61 dataset. This database is compiled from a research work developed at Azad University at Science and Research Branch, Tehran (Ebrahimabadi, 2010). Table 2 presents basic statistical descriptions on the existing dataset. As seen in Table 2, the dataset comprises of *UCS*, Brazilian tensile strength (*BTS*), *RQD*, the alpha angle (α) and also recorded *ICR*.

Table 2 Basic statistical descriptions on data set

Item	*UCS*	*BTS*	*RQD*	α	*ICR*
Mean	19.496 72	4.078 689	19.721 31	47.049 18	28.550 82
Median	16.400 00	4.000 000	19.000 00	47.000 00	25.700 00
Maximum	28.200 00	5.300 000	28.000 00	54.000 00	46.200 00
Minimum	14.100 00	3.600 000	18.000 00	39.000 00	14.600 00
Std. Dev.	5.443 680	0.306 113	1.826 939	4.835 377	10.194 99
Skewness	0.647 648	1.124 295	2.915 079	−0.173 019	0.247 247
Kurtosis	1.628 490	5.336 853	12.275 21	1.554 872	1.496 767
Jarque-Bera	9.045 371	26.730 81	305.051 4	5.612 348	6.364 926
Totaling	1 189.300	248.800 0	1 203.000	2 870.000	1 741.600

3 Roadheader performance predictive

The statistical based empirical equations are frequently employed to evaluate the influence of an input parameter on the output from a dataset. The empirical equations have great importance during the early stages of rock excavation and design works since this is a more practical way as compared with extensive and expensive experimental programs (Yagiz, 2008). In this paper, in order to perform statistical analyses on the dataset compiled from Tabas coal mine for predicting the roadheader performance, a commercial software packages for standard statistical analysis (SPSS) is applied. For achieving the aim, the correlation between the rate of the roadheader performance and each parameter is separately evaluated to construct a multiple variable regression (MVR) model.

4 Influence of rock mass properties on roadheader performance

In order to obtain the influence of each rock mass properties (*UCS*, *BTS*, α, *RQD*) on the roadheader performance, the correlations between these properties and the machine performance are investigated. It is generally believed that among the rock mass properties, the *UCS* is the most important parameters for roadheader performance prediction. However, this parameter cannot be reliable alone for the machine performance prediction, because the *UCS* is alone not able to represent all conditions of the rock mass. Besides, in this study, it is found that the relationship between the rate of the roadheader performance and *BTS*, α, and *RQD* are also not enough alone for the machine performance prediction.

The relationship between the *UCS* with the roadheader performance is significantly high with a correlation coefficient (r) of 0.953 as shown in Fig.3. As depicted in Fig.4, the *BTS* values have a linear relationship with the roadheader performance with r=0.71. The *RQD* values are weakly correlated with the rate of the machine performance that have an exponential correlation with r=0.265 (Fig.5). The results demonstrate that the correlation between the alpha angle and the roadheader performance are exponentially with r=0.67 (Fig.6). Obtained equations for calculating the rate of the roadheader performance as a function of each rock mass properties are presented in Table 3.

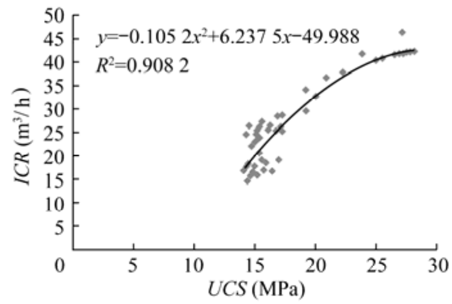

Fig.3 Quadratic relation between recorded *ICR* and *UCS* (r=0.953)

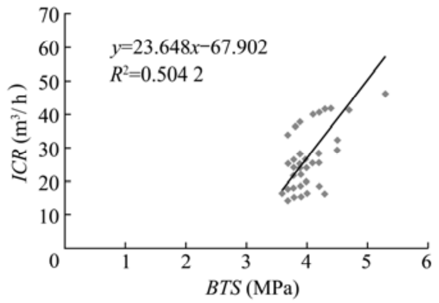

Fig.4 Linear relation between recorded *ICR* and *BTS* of rock (r=0.71)

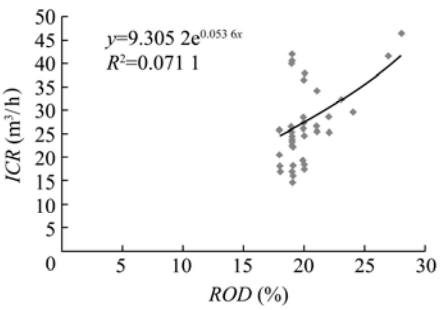

Fig.5 Exponential relation between recorded *ICR* and *RQD* (r=0.265)

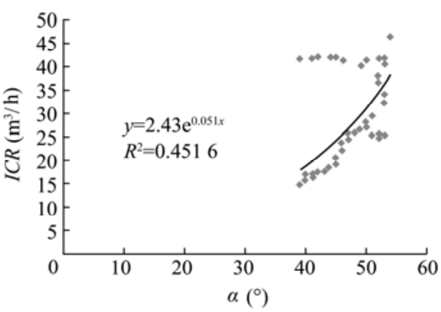

Fig.6 Exponential relation between recorded *ICR* and *α* (r=0.67)

Table 3 Equations between rock mass parameters and the recorded roadheader performance

Parameter	Regression type	Equation	Coefficient of correlation
UCS (MPa)	Quadratic	$y=-0.105x^2+6.237\,5x-49.988$	0.953
BTS (MPa)	Linear	$y=23.648x-67.902$	0.71
RQD (%)	Exponential	$y=9.305\,2e^{0.053\,6x}$	0.265
α (°)	Exponential	$y=2.43e^{0.051x}$	0.67

5 Multivariate regression (MVR) analysis

In this study, multivariate regression (MVR) analysis is carried out to find a robust equation between different rock mass properties against the roadheader performance with the best fitness. To achieve the aim, the four rock mass properties including *UCS*, *BTS*, *RQD*, and *α* are input parameters to assess the *ICR* chosen as output parameter.

After checking different combinations of parameters as presented in Table 4, the best fit regression between the input parameters in a linear combination with a 95% confidence level is related to the model 4 in which the four input variables *UCS*, *BTS*, *RQD*, and *α* as predictors and the *ICR* as response parameter exhibits the best fitted equation. As a result, the predictive equation is obtained as follows:

$$ICR=1.759UCS+0.501+0.636RQD-4.839\times BTS-22.127 \tag{1}$$

Based on the statistical results, the coefficient of determination (R^2) is 0.957. It indicates that the constructed model explains 95.7% of the total variance of the 61 datasets.

Table 4 Significance coefficients for each generated model

Model	Variables	Coefficients	Std. error	*t*-value	Sig.	*R*-squared	*F*-statistic	Prob (*F*-statistic)
1	*UCS*	−5.875 763	1.643 757	−3.574 593	0.000 7	0.889	472.27	0
	(Constant)	1.765 763	0.081 252	21.732 00	0			
2	*UCS*	−28.501 70	2.962 193	−9.621 823	0	0.949	539.01	0
	(Constant)	1.556 949	0.061 051	25.502 49	0			
	α	0.567 430	0.068 731	8.255 783	0			
3	*UCS*	−32.123 79	3.667 432	−8.759 207	0	0.951	370.55	0
	(Constant)	1.563 106	0.060 310	25.917 71	0			
	α	0.519 068	0.073 954	7.0187 50	0.			
	RQD	0.292 954	0.179 409	1.632 882	0.108 0			
4	*UCS*	−22.126 91	4.992 160	−4.432 332	0	0.957	312.761 1	0
	(Constant)	1.759 384	0.090 683	19.401 51	0			
	α	0.501 131	0.070 226	7.135 976	0			
	RQD	0.635 585	0.209 591	3.032 510	0.003 7			
	BTS	−4.839 031	1.738 264	−2.783 830	0.007 3			

6 Validation of the new predictive model

On the bases of the *t*-test analysis, it can be determined that the coefficient of correlation is true or not. According to this analysis, if the computed *t*-value is greater than the tabulated *t*-value, the null hypothesis is rejected that represents *r*-value is significant; otherwise it is not significant (Yagiz, 2008). As shown in Table 4, it can be seen that each one of the constructed models has the specific tabulated *t*-values that are different from other models on account of their difference in the number of input variables. Based on the tabulated *t*-values extracted from the reference table, it is demonstrated that the best model is the model 4 among the constructed models with the top score of *r*-value and a corresponding critical *t*-value is ±2.776.

In addition to the significant test of the coefficient of correlation, the significance of the regressions should also be tested. For this reason, the *F*-test analysis (analysis of variance) is accomplished. According to this analysis, if the tabulated *F*-value be smaller than the calculated *F*-value, the null hypothesis is rejected. From Table 4, it is evident that there is a real relationship between roadheader performance (*ICR*) and input variables (*UCS*, *BTS*, *RQD*, and α).

According to tabulated *F*-value extracted from the reference table, it is demonstrated that the best model is the model 4 among the models with the *r*-value of 0.978 and the corresponding critical *F*-value is ±2.45. Therefore, based on the values of *t*-test and *F*-test analysis, the results indicate that the coefficients are true and the correlations are real.

7 Conclusions

Based on data compiled from Tabas underground coal mine, a new predictive equation based on rock mass property is proposed to predict roadheader performance as a function of four rock properties, including *UCS*, *BTS*, *RQD*, and α. In the proposed model, the most effective parameters on the roadheader performance are *UCS* and α; whereas, *RQD* is the least effective. Likewise, the *ICR* is logarithmically increased when *UCS* ranges from 14.1 to 28.2 MPa. The *BTS* and the *ICR* have a logarithmic relationship, and the *ICR* increases with *BTS*. The α parameter plays a critical role in the *ICR*, and the *ICR* increases with α. The *RQD* does not have a significant impact on the *ICR*. It should be noted that the proposed model is extracted based on the dataset compiled from one underground mining project and should be employed with care although this study is accurately fulfilled in detail and the results are reliable and precise enough for roadheader performance prediction. It can be proposed for further researches to update the equation by new data to be used more confidently.

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