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A Statistical Model for Prediction TBM Performance using Rock Mass Characteristics in the TBM Driven Alborz Tunnel Project

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Abstract: This study presents an attempt to model the TBM performance with respect to the rock mass characteristics and site conditions of Alborz Service Tunnel. Alborz Service Tunnel is the longest tunnel (6.4 km and diameter 5.20) along Tehran Shomal Freeway in Iran. Many models and equations have previously been introduced to estimate penetration rate of TBM based on properties of both rock and machine employing various statistical analysis techniques. The statistical prediction model is set up by performing multi-linear regression analysis techniques. In this study evaluate the rock mass characteristics such as UCS, volumetric joint count (Jv), Joint Spacing (JS) and orientation of discontinuities in rock mass (α) on machine performance based on the information obtained from field observations and geotechnical site investigations. A comparison between the measured PR and predicted PR show that the correlation coefficient (R) between the predicted and measured PR is 0.84 (R = 0.84).

Keywords: TBM, penetration rate, regression.

INTRODUCTION

Performance of a TBM in a given project depends on many factors which can be classified in three categories:

- Machine specifications,
- Ground characteristics and
- Operating (Hassanpourm *et al*., 2009).

Many researchers have worked on development of new TBM performance prediction models or modification and adjustment of existing models. Ribacchi and Lembo-Fazio (2005), evaluated the relationship between RMR and performance of a double shield machine inthe Varzo tunnel (Ribacchi and Lembo-Fazio, 2005). Also Sapigni *et al*. (2002) studied the empirical relation between RMR and penetration rate (Sapigni et al., 2002). Cassinelli et al. (1982) used correlation between Rock Structure Rating system (RSR) and actual TBM performance to evaluate the penetration rate (Cassinelli et al., 1982).

Sanio found strong correlations between Uiaxial Compressive Strength (UCS) of rock and the specific energy defined as the amount of energy needed to excavate a unit volume of rock (Sanio, 1985). Bruland (1998) updated and improved the NTNU model (introduced by Blindheim 1979) based on field data mainly collected from Norwegian tunnels (Bruland, 1998). Rostami and Ozdemir (1993) developed the CSM model for cutting force estimation of disc cutters based on the Brazilian Tensile Strength (BTS) and UCS of rock (Rostami and Ozdemir, 1993). Subsequently, Yagiz (2002) modified the CSM model adding rock mass properties as an input parameter into the model (Yagiz, 2002). Ramezanzadeh et al. (2008) has also followed up on this work and developed a database of TBM field performance for over 60 km of tunnels. Then, he offered adjustment factors for CSM models to account for joints and discontinuities (Ramezanzadeh et al., 2008). Barton (1999, 2000) reviewed a wide range of TBM tunnels to establish the database for estimating penetration and advance rate (Barton, 1999). Yagiz (2008) has also performed statistical analysis on data obtained from Queens's tunnel (New York) and proposed an empirical model to predict TBM penetration rate. He has related four rock mass parameters (UCS, Punch test index or PSI, spacing and orientation of joints) to penetration rate of machine (Yagiz, 2008). In a similar research study, Gong and Zhao (2009) by performing a nonlinear regression analysis on data obtained from two tunnels excavated in granitic rock masses in Singpore developed an empirical equation to estimate bore ability of rock mass (Gong and Zhao, 2009).

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Fig. 1: Project Location of Alborz Service Tunnel (Wenner and Wannenmacher, 2009)

It is clear that proper evaluation of rock mass characteristics can also play a major role in machine operation to achieve the best performance. The prediction of TBM performance requires the estimation of Penetration Rate (PR), the ratio of excavated distance to the operating time during continuous excavation phase and Advance Rate (AR), the ratio of both mined and supported actual distance to the total time. In fact, most of the predictive models are concerned with the estimation of PR (Yagiz, 2008).

Among these models, some are based on laboratory cutting tests and some based on practical tunnel construction data. All the TBM performance prediction models can be divided into two distinguished approaches, namely, theoretical and empirical ones (Rostami and Ozdemir, 1993). Some of the models performed base on rock mass characteristics and some are base on rack mass classification. The main factors of rock mass properties used to predict the Penetration Rate (PR) in these models include the compressive strength and tensile strength of the rock material and the frequency and orientation of the rock joints (Gong and Zhao, 2009). Uniaxial Compressive Strength (UCS) of rock is the most widely used input parameter for predicting the TBM performance due to its easy measurement, a variety of experimental tests (i.e., Brazilian Tensile Strength (BTS), Schmidt hammer, Taber abrasion, point load index, Shore hardness, Drilling Rate Index tests) has been also used to estimate the performance of boring machines (Blindheim, 1979). The main rock mass classification systems used to predict performance include RSR (Rock Structure Rating) (Cassinelli *et al*., 1982). RMR (Rock Mass Rating), Q (Rock Mass Quality Indexsystem and IMS (integrated mass system). The present study was attempted to develop more accurate and practical predictive equation base on rock mass properties in hard rock condition (Gong and Zhao, 2009).

CASE STUDY (ALBORZ TUNNEL)

The Tehran Shomal Freeway project in Iran is a new freeway to connect the capital Tehran with the city of Chalus at the Caspian Sea in the North. The total length is 121 km. currently traffic runs on small roads passing the Alborz Mountains and the journey takes 5 - 6 h. Upon completion of the project the travelling time will reduce to less than 2 h with an overall higher capacity. The freeway alignment has more than 30 twin tunnels for double lanes. The Alborz Tunnel will be the longest of these with a length of 6400 m at an altitude of 2400 m, Fig. 1. The paper covers the TBM excavation of the service tunnel (Wenner and Wannenmacher, 2009).

The service tunnel is located between the main tunnel tubes and is used for site investigation, drainage and as access for the main tunnel construction to commence soon, as well as for ventilation and later as a service tunnel for the main tunnels during operation. The length of the service tunnel is 6387 m, including 314 m of drill and blast tunnel previously excavated from the south portal and 46 m for the TBM starting tube from the N-portal. An open gripper hard rock TBM from Wirth (5.2 m diameter) has started excavation at TM 46 from north

Table 1: Summary of albora long tunnel and tunneling machine parameters (Wenner and Wannenmacher, 2009)

Parameter	
Total tunnel length (km)	6.3
Excavated tunnel diameter (m)	5.2
Tunnel slope (%)	1
TBM type	Open
TBM model	Wirth
Number of cutters	40
Cutter diameter(mm)	432
Maximum cutterhead torque (Knm)	1260
Cutterhead power (KW)	1500
Thrust force (KN)	8400
Rotational speed (rpm)	0-8.6

portal (= TM 0) with constant positive gradient (~1%). The maximum overburden is in the range of 850 m. Descriptive information on the Zagros tunnel and tunneling machine is summarized in Table 1.

Site investigation for the service tunnel included a geological surface mapping, a geoelectric resistivity survey along the alignment from the surface and some index laboratory tests on rock samples. The service tunnel itself is the site investigation for the main tunnels. Geological conditions are complex and overall heterogeneous. In the north, there are Triassic and Jurassic argillites with some sandstone and thin coal layers of Shemshak formation, followed by sandstone and then limestone formation. At TM ~3800, a 300 m there are thick fault zone, representing the Kandovan fault zone with a vertical displacement of some km. No further information or details were available on this zone.

Further south, Oligocene clastic sediments (Kandovan Shale) were predicted, including massive gypsum / anhydrite bodies with a length up to 300 m on tunnel level. At the surface the gypsum shows massive karstic features with unknown extend below surface (overburden ~600 m above tunnel level). The remainder of the tunnel is Eocene tuffs, shales and other layered rocks of Karaj Formation. Fig. 2. Show longitudinal geological profile of Alborz tunnel Rock mass parameters for performance analysis (Wenner and Wannenmacher, 2009).

Rock mass properties: On the basis of effective parameter on penetration rate of TBM, main rock mass properties are presented. These parameters Include Uniaxial Compressive Strength (UCS), volumetric joint count (Jv), angle between tunnel axis and the planes of weakness (α) and Joint spacing (Js).

Rock strength: On the basis of effective parameter on penetration rate of TBM, main rock mass properties are presented. These parameters include Uniaxial Compressive Strength (UCS), volumetric Joint count (Jv), angle between tunnel axis and the planes of weakness (α) and Joint Spacing (Js).

This fact has been observed by many researchers that the rock strength is directly relevant to the performance of TBM. Some models for predicting PR show that the PR is directly relevant to rock uniaxial compressive strength (Graham and Bieniawski, 1976; Farmer and Glossop, 1980). Generally, the PR decreases with the increase of rock uniaxial compressive strength.

Volumetric joint count (jv): The volumetric joint count (Jv), defined as the sum of the number of joints per cubic meter for each joint set present. According to this definition, below equation is derived; it takes into account all the joints and fractures encountered (Gong and Zhao, 2009):

$$J_v \Sigma \left(\frac{1}{J_{si}} \right) + \left[\frac{N_{r(5)} + N_{r(10)}}{5} \right]$$

where,

JSI = The joint spacing in meters for the actual joint set Nr (5) or

Nr (10) = The number of random joints along 5 or 10 m perpendicular to the sampling lines

Joint spacing: Rock masses are composed of rock material and joints, the existing joint conditions certainly affect the rock breakage process. It is easy to be understood that discontinuities can facilitate rock breakage, because cracks induced by TBM cutters easily develop along with the existing discontinuities (Gong and Zhao, 2009). In practice, Type and density of discontinuities have a crucial importance on both the behavior of a rock mass and machine advancement. On the basis of a large number of case histories Bruland concluded that with the decrease of joint spacing, the TBM penetration increases distinctly (Bruland, 1998).

Angle between tunnel axis and the planes of weakness (α): In order to be able to quantify the influence of discontinuity properties on TBM performance, the alpha angle that is the angle between tunnel axis and the planes of weakness have been used. The (α) angle, have been measured in the field by measuring strike and dip of the joints mapped at the face. The α in degrees, can be calculated using the following equation (Bruland, 1998):

$$\propto = \mathit{Are}\ \sin(\sin \propto_f \ \sin(\propto_t - \propto_s)$$

where,

αf = Dip of encountered planes of discontinuities

αs = Strike of encountered planes of discontinuities

αt = Direction of the tunnel axis in degrees

Database: Because develop model, a database including rock mass properties and the measured TBM performance

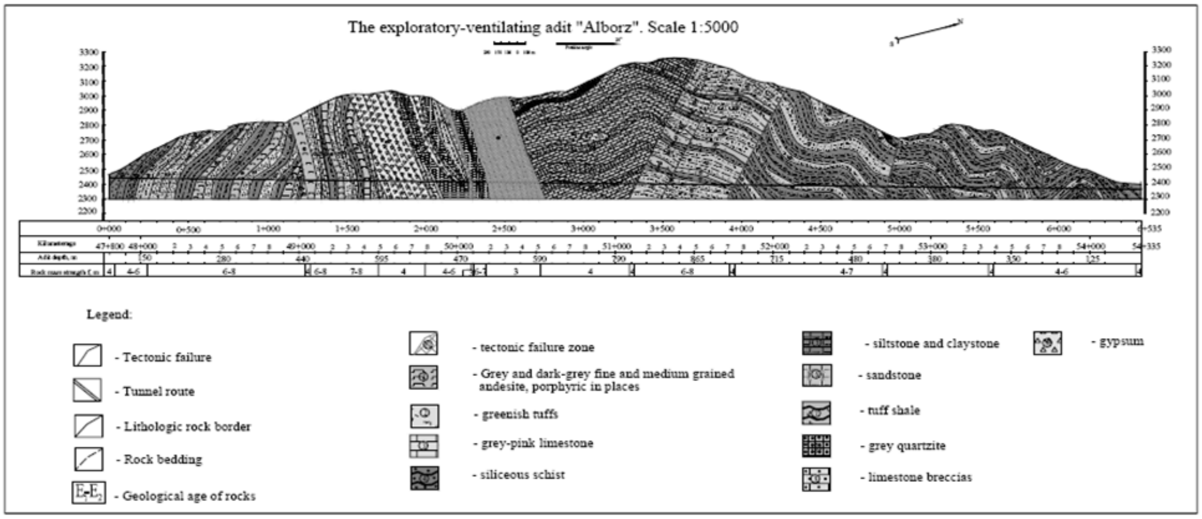

Fig. 2: Show longitudinal geological profile of Alborz tunnel (Wenner and Wannenmacher, 2009).

Table 2: Descriptive statistics of generated database for this study.

	Range	Min.	Max.	Mean	S.D.	Variance
measured PR (m/h)	1.35	1.85	3.20	2.441	5.35431	0.126
UCS(Mpa)	105	40	145	86.09	23.171	536.912
Jv (number/m^3)	12.5	7.5	20.0	13.65	42.6159	6.843
Alfa (deg)	47	28	75	51.05	9.325	86.961
Js (cm)	24	20	44	30.63	5.571	31.040

parameters including penetration rate (PR) was established. Data for analysis have been collected from 85 different locations along Alborz tunnel. The database is analyzed progressively to further set up a function for the prediction of TBM penetration rate. Descriptive statistical distribution of variables in the database and input parameters for generated models is summarized in Table 2.

Properties of intact rocks and discontinuities in rock masses: According to Table 2 average of Rock strength (UCS) is 86 Mpa and limited between 40 and 145 Mpa. The UCS mainly concentrates between 70 and 110 MPa. And range of the angle between the tunnel axis and the joint plane, which is mainly distributed between 10 and 80 degree. As the angle is close to 90, it is difficult to be observed at the tunnel face. And range of the volumetric joint count (Jv) and joint spacing (Js) are between 7.5 to 20 and20 to 42 cm, respectively.

Tbm penetration data: The excavation of the rock by TBM is expressed in the penetration rate. Data for compose database of penetration rate have been obtained from daily report of Alborz long tunnel.

Simple regression: After select parameter and establishment of the database, one of the commercial Software Packages for Standard Statistical analysis (SPSS) was used to perform the simple and multiple variable regression analysis between independent (UCS, Jv, α and Js) and dependent (PR) variables.

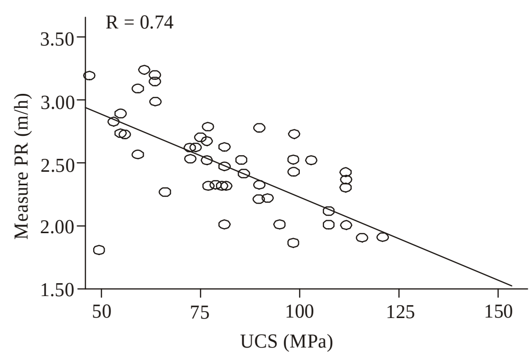

Fig. 3: The relationship between measured PR and UCS

In the first stage of the analyses, a series of simple regression analyses between the independent variables and the dependent variable was conducted. The simple regression analyses provide a means of summarizing the relationship between two variables. During the simple regression analyses, linear, power, logarithmic and exponential functions were used.

After single regression analysis, best equations were selected with maximum correlation coefficient between independent variables and the de pendent variable. The relationship between UCS of rock with the PR was found very strong with a correlation coefficient (R) of 0.74

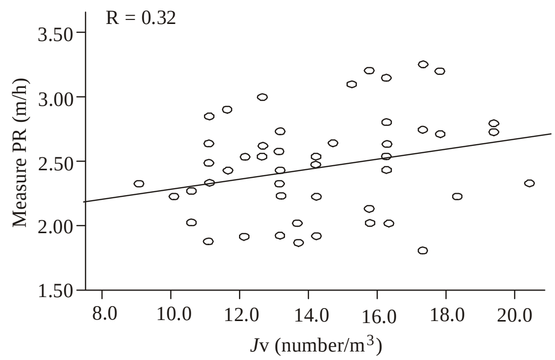

Fig. 4: The relationship between measured PR and Jv

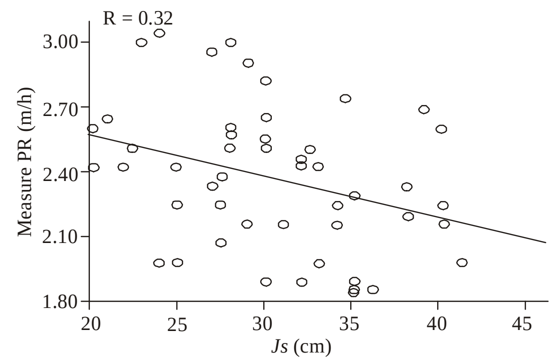

Fig. 5: The relationship between measured PR and Js

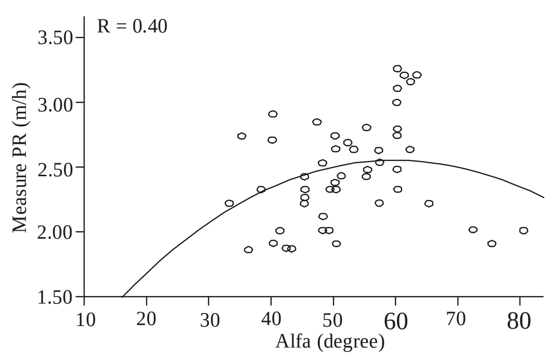

Fig. 6: The relationship between measured PR and α

which is an indicator of correlation strength. Fig. 3. illustrate the correlations between UCS and the actual measured PR.

The effect of volumetric joint count (Jv) on the PR is shown in Fig. 4. The PR increases with increasing (Jv). The relationship between Jv and actual measured PR is linear and correlation coefficient (R) is 0.32 (Fig. 4).

According to prospect with the increase of Joint spacing (Js), the TBM penetration decrease distinctly. The relationship between Js and actual measured PR were obtained with an r = 0.32 as shown in Fig. 5.

Table 3: Correlation coefficients of the relations among the independent variables.

variable	UCS	Jv	Js	α
UCS (Mpa)	1.0	0.01	0.08	0.063
Jv (number/m3)	-	1.0	0.68	0.1
Js (cm)	-	-	1.0	0.18
A angel (degree)	-	-	-	1.0

Against relationships between UCS, Jv and Js with measured PR, The result demonstrated that the α angle and measured PR have quadratic relationship with an r =0.4 (Fig. 6). Relationship between PR and angle illustrated in Fig. 6. is almost consistent with that of the results of field studies by Bruland (1998) and Yagiz (2008) and numerical simulations by Gong and Zhao (2009) and Khademi et al. (2010) (Khademi et al., 2010). The best TBM performance occurs at α angle between 50 and 70 degree. As seen from Fig. 6, the maximum PR could be obtained as the angle 60 degree.

Obtained equations between the ROP and each rock parameters are demonstrated in below:

$$PR = -0.12UCS + 3.456$$
$$PR = 0.046Jv + 1.815$$
$$PR = 0.046Js + 3.102$$
$$PR = 0.0087 \propto^2 + 0.104 \propto 0.54$$

where,

PR = Penetration rate (m/h)
Jv = Volumetric joint count (number/m3)
Js = Joint spacing (cm)
α = Angle between tunnel axis and the planes of weakness (degree)

Survey relations among the independent variables: To prevent redundancy in the models, the relationship among the independent variables was investigated. It was therefore decided to check the relationships between the independent variables on a one to one basis. As demonstrated in Table 3 This led to finding a high correlation between Jv and JS with Correlation coefficients (R) of 0.68 in this particular case study. However, most variables have some correlation due to the nature of observational data. Accordingly, one of these two variables should be excluded from the independent variables set. From the analysis of the coefficient of the correlation, the variable JS was chosen to be excluded from new multi-linear regression model.

Linear multiple regression analyses: The new regression model was obtained by excluding JS from independent variables list. To consider the effects of intact rock and rock mass properties together on the PR, the

Table 4: Significance and coefficients for each generated model.

	Unstandardized Coefficients			Standardized Coefficients		
Model	B		S.E	β	t	Sig.
1	(Constant)	3.479	0.132		26.273	0.000
	UCS	-0.012	0.002	-0.749	-8.072	0.000
2	(Constant)	2.823	0.199		14.189	0.000
	UCS	-0.013	0.001	-0.760	-9.339	0.000
	Jv.	048	0.012	0.330	4.053	0.000
3	(Constant)	2.390	0.227		10.508	0.000
	UCS	-0.012	0.001	-0.753	-10.072	0.000
	Jv	0.042	0.011	0.292	3.855	0.000
	Alfa	0.010	0.003	0.242	3.201	0.002
4	(Constant)	2.602	0.415		6.266	0.000
	UCS	-0.012	0.001	-0.748	-9.898	0.000
	Jv	0.037	0.014	0.255	2.648	0.011
	Alfa	0.009	0.003	0.231	2.949	0.005
	Js	-0.004	0.007	-0.061	-0.611	0.544

* Dependent Variable: measured PR

linear multi-variable regression analyses were performed. To achieve this aim, the Threeengineering rock properties (UCS, Jv, α) were input as dependent variables and the measured PR were chosen as an independent variable. Influence of each variable on the PR was evaluated using forward stepwise regression analyses (Table 4).

From the statistical analysis, the four predictive models of linear multiple regressions after enter variables is as follows:

$$PR = -\ 0.012UCS + 3.49$$

(R = 0.74)

$$PR = -\ 0.012UCS + 0.048J_v + 2.82$$

(R = 0.74)

$$PR = -\ 0.012UCS + 0.042\ J_v + 0.01 \propto +2.39$$

(R = 0.74)

where,

PR = Penetration rate(m/h),
Jv = Volumetric joint count (number/m3)
Js = Joint spacing (cm)
α = Angle between tunnel axis and the planes of weakness(degree)

In the models, the maximum correlation coefficient (r = 0.85) was obtained in model 3, which selected UCS, Jv and α angle as input variables.

According to Table 3 model 4 was obtained while Js is in the independent variables set. Whereas correlation coefficient (R = 0.852) of model 4 is higher than other models but t-test isn't significance ($p > 0.05$) that it means that model 4 because high correlation between Jv and Js is explained in section 5, is rejected. But t-test of model 3 is significance it means the null hypothesis is rejected and model 3 acceptable.

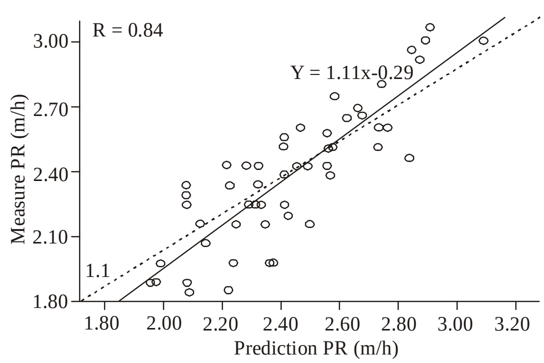

Fig. 7: Comparison between the measured and predicted PR.

Compare measured pr with predicted pr: A comparison between the measured PR in field and predicted PR by Linear multiple regression was carried out. Results compare is shown in Fig. 7.
The correlation coefficient (R) between the predicted and measured PR is 0.84 and the slope of trend line is more than 1:1, which means that the measured PR is almost more than the predicted PR.

CONCLUSION

Based on data obtained from 6.3 km of Alborz tunnel in igneous and sedimentary rocks, a database including rock mass properties and the measured TBM performance parameters was established(UCS, Jv, Js, α and measure PR). Simple regression results indicated that correlation of UCS with measured PR is higher than other parameters. The UCS, Jv and Js have a linear relationship with PR and the PR increases with decrease UCS and Js and increase Jv. The result demonstrated that the α angle and measured PR have quadratic relationship and the best TBM performance occurs at α angle 60 degree. Inter-correlation between independent variables (Jv and JS) led to exclusion of JS from the Linear multiple regression analysis and formulas. A multi-variable linear regression showed the best correlation between the measured PR and three input parameters, with correlation coefficient of 0.85. Finally two measure PR and prediction PR were compared, with correlation coefficient of 0.84.

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