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Estimation of penetration rate of tunnel boring machines using Monte-Carlo simulation method

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Abstract

One of the most important parameters used for determining the performance of tunnel boring machines (TBMs) is their penetration rate. The parameters affecting the penetration rate can be divided in two categories. The first category is the controllable parameters such as the TBM technical characteristics, and type and geometry of the tunnel, and the second one is the uncontrollable parameters such as the intact rock properties and characteristics of the rock mass discontinuities. The aim of this work was to investigate the effects of rock mass properties on the penetration rate, and to present a new mathematical equation based on a statistical approach to estimate the TBM performance. To achieve this aim, the Monte-Carlo (MC) simulation method was used to model the TBM performance. Accordingly, the database consisting of the rock mechanics information such as the uniaxial compressive strength, Brazilian tensile strength, toughness and hardness of rock, spacing and orientation of discontinuities, and measured TBM penetration rate in 151 points out of a water tunnel was collected. Next, using the dimensional analysis, a comprehensive mathematical equation was obtained to calculate the TBM penetration rates using the developed database. Finally, using the MC simulation method, the probability distribution function of the TBM penetration rate was studied. The validation results obtained showed that the root mean square error (RMSE) of the proposed relationship was less than 0.3. The MC simulation results showed that hardness and density had the most and least effects on the penetration rate, respectively.

Keywords: *TBM, Penetration Rate, Monte-Carlo (MC) Simulation, Dimensional Analysis.*

1. Introduction

One of the most important parameters used for determining the performance of tunnel boring machines (TBMs) is the penetration rate. Many factors are involved in the operation of rock excavation machines [1-5]. Among these, the major factors are rock mass characteristics, intact rock properties, geological properties, machine characteristics, operator skills, and expert knowledge. Moreover, the interaction between the machines and rock masses is dynamic, uncertain, complex, and non-linear. Furthermore, in most cases, rock masses are anisotropic, non-linear, and discontinuous. Generally, the most relevant factors influencing the penetration rate can be classified into three categories: rock mass properties, machine characteristics, and geometry of the tunnel [6]. Rock mass properties are determined by the intact rock and discontinuity structure of the rock mass. The most important intact rock parameter that influences the penetration rate is the rock strength (UCS); the greater the rock strength, the lower the penetration rate is. In some cases, the presence of discontinuities weakens the rock mass, increasing the penetration rate. The most important machine technical characteristics that affect the TBM penetration rate are the type and diameter of cutter disk, thrust force of each disk, cutter spacing, and operator skills. Geometry of the tunnel has turned out to be a very important parameter. Many parameters such as RPM, torque, and total power consumption are influenced by the geometry of the tunnel. In general, it can be said that the penetration rate per length decreases with increase in diameter [7]. Figure 1 shows the main factors influencing the penetration rate .

Taking the highly important TBM penetration rate into consideration, a considerable amount of study has been carried out by so many researchers to find a relationship between the aforementioned parameters in order to predict this rate. Tarkoy (1973) has presented a model to predict the penetration rate, which uses only the total hardness as a predictor parameter [8]. A major disadvantage of the Tarkoy's model is that it considers neither the rock mass characteristics nor the machine characteristics, which are very important in the overall performance of TBMs. Graham (1988) has introduced a model in which the penetration rate is computed as a function of the normal force per cutter, the RPM, and the unconfined compressive strength of the tunneled rock. The model considers neither the discontinuities nor the cutter properties [9]. Bruland et al. (1988) have, however, indicated that zero and ninety degrees are the only extreme values, and that the discontinuity effects can be more influential between these two angles. Furthermore, the spacing of the planes of weakness influences the penetration rates considerably [10]. Innaurato et al. (1991) have introduced an updated version of the method presented by Cassinelli et al. (1982). The method includes the rock structure rating (RSR) of Wickham et al. (1974). The major change in the updated method is the incorporation of the unconfined compressive strength of the rock [11-13]. Chiaia (2001) has incorporated a lattice model into the FEM program to model the penetration process in a heterogeneous material by a hard-cutting indenter. It has been revealed that the dominant modes of the indentation mechanisms are the plastic crushing and brittle chipping [14]. Using the discrete element method (DEM), Gong et al. (2005) have presented a series of 2D numerical modeling to explore the effect of joint orientation on rock fragmentation by a TBM cutter. The results obtained show that the joint orientation can significantly influence the crack initiation and propagation as well as the fragmentation pattern, and hence affect the penetration rate of TBM [15]. Gong and Zhao (2006) have analyzed the influence of rock brittleness on the rock fragmentation process using the UDEC modeling. The results obtained show that with increase in the rock brittleness index, the crushed zone and radial cracks increase. The failure element induced by the cutter increases almost linearly with increasing rock brittleness index. It clearly indicates that with this increase, the rock breakage process becomes easier. By the statistical analysis of the rock mass properties and TBM performance in the study, it was found that the TBM penetration rate increased with increasing rock brittleness index [16]. Ma et al. (2011) have investigated the effect of confining stress on the rock fragmentation under TBM cutters by numerical simulation. The results obtained show that the confining stress has a significant impact on the key factors for rock fragmentation including the chipping force, crack angle, effective crack length, and energy dissipation. Specifically, the chipping force and crack angle increase with the rising confining ratio [17]. Khademi hamidi et al. (2011), in their research work, have investigated the recent penetration rate estimation attempts [18]. Hassanpour et al. (2011) have presented a bore-ability classification system and a new empirical chart for the preliminary estimation of rock mass bore-ability and TBM performance [19]. Farrokh et al. (2012) have presented a new equation to estimate the TBM penetration rate [20]. Medel-Morales and Botello-Rionda (2013) have used the discrete element method (DEM) to build models that simulate the rock cutting process under a cutting disk, and measure the interaction between forces and hard rock, which is essential for the design of TBMs [21].

Although numerous methods have been proposed for predicting the performance of TBM, it is evident that there is no unique and comprehensive approach to model the performance of TBM in real-world projects. Often, the disadvantages of these methods are that they neglect the rock mass characteristics, which are very important in the overall performance of TBMs. The most appropriate method used for the effective estimation of the penetration rate of TBM must consider all the parameters that influence the penetration rate simultaneously.

This study attempts to develop a new practical predictive equation, especially for estimating the TBM penetration rate, using the dimensional analysis and MC simulation methods. In order to validate the provided mathematical equation, the simulation results obtained for the penetration rate by the MC method were compared with the values measured for the TBM penetration rate in the studied area.

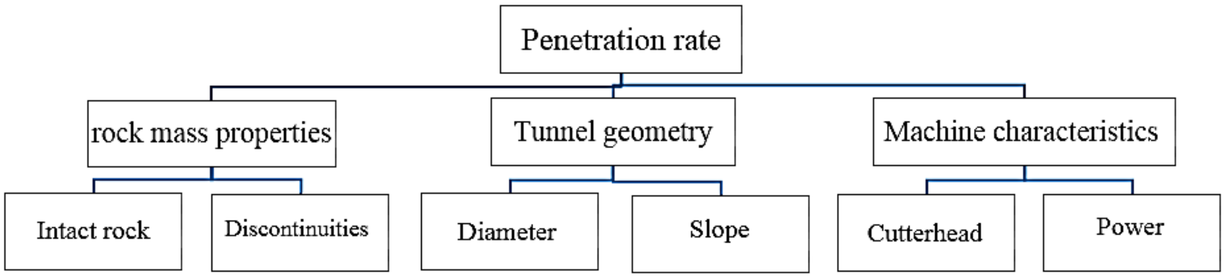

Figure 1. Main factors influencing penetration rate.

2. Methodology

2.1. Dimensional Analysis

Dimensional analysis is an engineering method used for creating equations that simplify the analysis of complex multivariable systems [22–25]. Dimensional analysis has its origin in the work of Maxwell, who used the symbols [F], [M], [L], [T], and [Q] to denote force, mass, length, time, and charge, respectively. Lord Rayleigh has used it extensively in his 'theory of sound', calling it 'principle of similitude' or 'method of dimensions' [24]. He was famous for writing the following statement, testifying the power of the method: ''It happens not infrequently that results in the form of laws are put forward as novelties on the basis of elaborate experiments, which might have been predicted a priori after a few minutes consideration''. Applications of the dimensional analysis to the engineering problems have been conducted by well-known scholars such as Einstein and Reynolds. The method of dimensions was developed over time to include many sub-techniques. First, it was used to derive the dimensionless groups. Then it was utilized for scale-up purposes so that small-scale models can be extrapolated to real-life models. This evolved to the point where the dimensional analysis was used for appropriate scaling. Through scaling, it is possible to judge. Scaling leads to the useful concept of the order of magnitude. It is useful because it is possible to compare two phenomena and decide whether they are relevant, comparable or irrelevant. This engineering judgment is critical in reducing the physical complexity of the problem to be solved [26]. For example, when a process involves a number of factors, the order of magnitude helps in finding which factors are dominant and which ones are irrelevant or negligible.

One of the best techniques or variations used for carrying out a dimensional analysis is the Buckingham π-theorem. This theorem (also written as the Pie-theorem) states that if n measurable quantities (or variables) form a complete functional relationship $\phi(\alpha,\beta,\gamma,...)=0$, then the solution has the form $f\left(\pi_1,\pi_2,\pi_3\right)=0$, where the π's are then the n–m independent products of the arguments α,β,γ, etc., which are dimensionless in the fundamental units required to measure the quantities. It is called complete because the relationship consists of sufficient fundamental dimensions to describe the magnitude of the quantity of interest. Thus the dimensionally homogeneous equation $\phi(\alpha,\beta,\gamma,...)=0$ is reduced to a relationship among a complete set of dimensionless products, referred to as the π terms, and the number of members (terms) of the set is equal to the number n of measurable quantities/variables minus the number of fundamental units m involved in measuring the variables. The dimensional matrix has the variables as the column/row headings and the fundamental dimensions forming the rows/columns.

The application of dimensional analysis goes through several steps. First, all the variables involved in the phenomenon are listed. Since the dimensional analysis finds the minimum number of groups based on primary dimensions, close attention needs to be paid to make sure that only relevant quantities are included and physical irrelevant independent variables are discarded. A physically irrelevant variable has a sufficiently small influence on the dependent variable (the target variable). We can also recognize a physically irrelevant variable through physical insight of the problem at hand or through experimental investigations. At this stage, one has to be careful about the linear dependency among parameters, after which, the dimensional matrix is assembled (sometimes called the constitutive matrix). Once the matrix is assembled, a number of techniques and conditions help one proceed, and these depend on the number of dimensions involved with respect to the number of variables. When the equations governing the process are provided, then the dimensionless groups can be set to 1 for scale factors, and to zero for reference factors. This usually leads to the minimum parametric representation. The π's include dimensionless groups which are made from combining the geometric and physical quantities and other dimensionless independent variables. Figure 2 shows the algorithm of the dimensional analysis method.

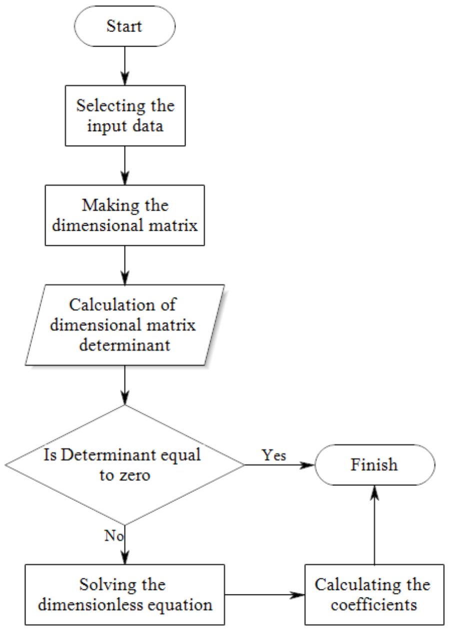

Figure 2. Dimensional analysis method algorithm.

2.2. MC Simulation

The MC method is one of the most capable approaches used for solving and analyzing the complex problems. This method is applicable in various fields of mining engineering. It has many advantages in comparison to the traditional methods, among which the following can be pointed out: its independence with respect to time, its ease of application, and its ability to combine the experience and statistical observations. Moreover, in the traditional methods, analyzing a complex process with numerous uncertain variables is impossible but the MC simulation method has the ability to solve these problems and to investigate the effects of interactions between its parameters. The algorithm for the TBM penetration rate simulation using the MC method is shown in Figure 3.

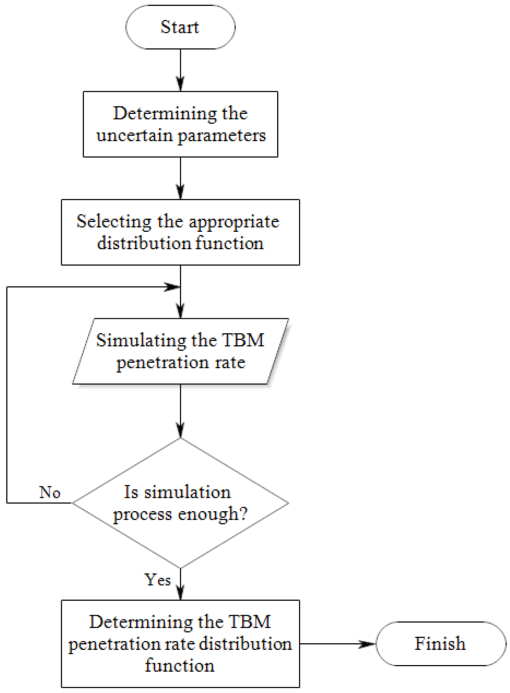

Figure 3. Algorithm of TBM penetration rate simulation.

3. Numerical Analysis

In this section, at first, a new mathematical equation is suggested to calculate the TBM penetration rate using the dimensional analysis, and then the penetration rate distribution function is determined using the MC simulation approach.

3.1. Data Collection

In order to develop a mathematical equation for calculating the TBM penetration rate, the data sets from Queens Water Tunnel # 3, stage 2, located in the New York City in USA were used. These data sets have been published in Yagiz (2008) [27]. The tunnel being about 7.5 km long and 7 m in diameter was excavated beneath Brooklyn and Queens at an average depth of 200 m below the sea level in the west-central Queens County using a high power TBM [27].

In the studied area, the geological formations are highly complex, and are composed of different metamorphosed igneous rock with shear zones, joint, faults, and other local weakness zones. Five main geological formations have been identified in the studied area as follows: the Manhattan schist is composed of gray, medium to coarse-grained layered schist and gneiss. The Inwood formation includes different types of marble units of white coarse-grained calcite–dolomite marble. Hartland formation mainly consists of gray and gray-weathered thinly-laminated muscovite–biotite–quartz schist with minor garnet. The

Fordham gneiss is a highly complex unit that includes black hornblende–biotite gneiss and white quartz plagioclase moderately banded gneiss [28].

In order to carry out intact rock property tests including the BTS, UCS, and punch penetration tests, rock cores were taken from the tunnel side at 151 different locations throughout the fractured hard rock tunnel. Intact rock strength tests (UCS and BTS) were employed in accordance with the procedures suggested by ASTM [29-31]. The punch penetration test, used for investigating rock brittleness and toughness, was performed according to the recommended industrial testing standard previously discussed by different researchers [32-34]. The punch penetration test apparatus consisted of a stiff machine with hydraulic ram that pressed a tungsten carbide indenter into a saw cut surface of the sample. While performing the test, the displacement of the indenter into the sample and the load on the indenter were monitored, and consequently, the load versus penetration graph was made. On this graph, the ratio of the maximum load (in kN) applied to the specimen to the corresponding displacement (in mm), named as peak slope index (PSI), was used to quantify the rock brittleness and toughness.

The type and density of discontinuities have a crucial importance on both the behavior of a rock mass and machine advancement. In order to be able to quantify the influence of discontinuity properties on TBM performance, the alpha angle, which is the angle between the tunnel axis and the planes of weakness, was used. To calculate the alpha angle, the orientation of discontinuities and the driven direction of TBM were measured in the field. The alpha (α) in degrees can be calculated using the following equation [27]:

$$\alpha = \arcsin(\sin(\alpha_{\mathrm{f}}).\sin(\alpha_{\mathrm{t}} - \alpha_{\mathrm{s}})) \quad (1)$$

where α_{f} and α_{s} are the dip and strike of the encountered planes of weakness in rock mass, and α_{t} is the direction of the tunnel axis in degrees. Furthermore, NTNU developed a fracture class (FC) system for investigating the complex rock mass structures to be excavated by a TBM. In the Queens tunnel, the regional jointing pattern was not separated from the shear zones and faults, and thus combined effect of faults, shear zone, fissures, and joints on TBM penetration rate were evaluated. The FC system was slightly modified and used in the established database. In order to calculate the joints, spacing effect was used for the average distance between planes of weakness-DPW (m) [27]. The datasets used are shown in Table 1.

Table 1. Engineering rock properties, rock types, and measured ROP in the field [23].

Type of rock	ROP (m/h)	α (°)	DPW (m)	PSI (kN/mm)	BTS (MPa)	UCS (MPa)
Granitoid (felsic) gneiss and orthogneiss	2.19	25	0.80	55	9.3	199.7
Mafic-to-mesocratic orthogneiss	1.88	20	2.00	55	9.1	199.0
Mafic-to-mesocratic gneiss, amphibolite, and schist	2.20	40	2.00	56	9.0	189.0
Massive garnet amphibolite and larger mafic dikes	2.87	29	0.20	46	10.6	188.3
Rhyodacite dike rocks	2.47	15	0.10	36	7.7	140.7

3.2. Development of mathematical equation

In order to provide a mathematical relationship to calculate the penetration rate of TBM using the dimensional analysis, the input and output parameters were collected and presented in Table 2.

In the dimensional analysis, it is necessary to select a unit system, i.e. mass or force. In this paper, the mass system was chosen. In the next stage, all of the dimensional parameters had to be converted to the reference parameters. Accordingly, the dimensions of each input and output variable could be defined as follow: [ROP]= LT^{-1}, [α]=1, [DPW]= L, [γ]= ML^{-3}, [BTS]= $ML^{-1}T^{-2}$, [UCS] = $ML^{-1}T^{-2}$, and [PSI] = MT^{-2}, where M, T, and L represent the mass, time, and length, respectively. Since the alpha angle is without unit, this factor is a dimensionless parameter, and so in the calculation process was assigned the amount of 1. With the available variables, a lot of dimensionless combinations of complete sets could be constructed. However, as a first step, to make the dimensional matrix, the variables had to be arranged correctly. The dimensional matrix for ROP may be considered as follows (Table 3).

Table 2. Input and output parameters.

	Parameters	Symbol for parameters	Unit
Input parameters	Uniaxial compressive strength	UCS	MPa
	Brazilian tension strength	BTS	MPa
	Rock density	γ	Kg/m^3
	Brittleness and hardness of intact rock	PSI	KN/mm
	Distance between plates of weak	DPW	m
	Alpha angle	α	-
Output parameters	TBM penetration rate	ROP	m/h

Table 3. Dimensional matrix.

	ROP	DPW	PSI	α	BTS	UCS	γ
M	0	0	1	0	1	1	1
L	1	1	0	0	-1	-1	-3
T	-1	0	-2	0	-2	-2	0

To determine the rank of the matrix, the determinant parameters UCS, PSI, and γ were calculated.

$$\begin{bmatrix} 1 & 1 & 1 \\ 0 & -1 & -3 \\ -2 & -2 & 0 \end{bmatrix} = -2 \neq 0$$

The determinant was not equal to zero. Therefore, it could be concluded that the variables were selected correctly, and that the rows of the matrix were not linearly dependent.

The dimensional matrix included seven variables, and the rank of this matrix was 2. According to the π theorem, in a complete set, there should exist four dimensionless terms (7 - 3 = 4). π and homogeneous algebraic equations can be written by the dimensional matrix as follow:

$$\pi_1 = \alpha \quad (2)$$

$$\pi_2 = \pi_{ROP} = \left(MT^{-2}\right)^{K_1} \times \left(ML^{-1}T^{-2}\right)^{K_2} \times \left(ML^{-3}\right)^{K_3} \times \left(LT^{-1}\right) \quad (3)$$

$$\pi_3 = \pi_{DPW} = \left(MT^{-2}\right)^{K_4} \times \left(ML^{-1}T^{-2}\right)^{K_5} \times \left(ML^{-3}\right)^{K_6} \times \left(L\right) \quad (4)$$

$$\pi_4 = \pi_{\beta} = \left(MT^{-2}\right)^{K_7} \times \left(ML^{-1}T^{-2}\right)^{K_8} \times \left(ML^{-3}\right)^{K_9} \times \left(ML^{-1}T^{-2}\right) \quad (5)$$

The summation of the powers in Eqs. (3-5) had to be equal to zero. The summations of the powers of each parameter in Eq. (3) were as follow:

For T: $-2K_1 - 2K_2 - 1 = 0$

For M: $K_1 + K_2 + K_3 = 0$

For L: $-K_2 - 3K_3 + 1 = 0$

By solving the above equations, the powers were:

$K_1 = 0,\ K_2 = -\frac{1}{2},\ K_3 = \frac{1}{2}$

The summations of power for each parameter in Eq. (4) were as follow:

For T $-2K_4 - 2K_5 = 0$

For M: $K_4 + K_5 + K_6 = 0$

For L: $-K_5 - 3K_6 + 1 = 0$

By solving the above equations, the powers are:

$K_4 = -1,\ K_5 = 1,\ K_6 = 0$

The summations of power for each parameter in Eq. (5) were as follow:

For T: $-2K_7 - 2K_8 - 2 = 0$

For M: $K_7 + K_8 + K_9 + 1 = 0$

For L: $-K_8 - 3K_9 - 1 = 0$

By solving the above equations, the powers are:

$K_7 = 0,\ K_8 = -1,\ K_9 = 0$

By applying the power coefficients obtained, the relations 3 to 5 could be rewritten as the following forms:

$$\pi_2 = ROP \times UCS^{-1/2} \times \gamma^{1/2} \quad (6)$$

$$\pi_3 = PSI^{-1} \times UCS \times DPW \quad (7)$$

$$\pi_4 = BTS \times UCS^{-1} \quad (8)$$

In the next stage, it was considered whether the relationship was linear or non-linear. With the help of multivariable regression analysis from the collected data, the unknown coefficients could be determined. With a comparison made between the correlation coefficients (R^2) of the linear and non-linear equations obtained by SPSS version 20, it was concluded that the non-linear equation was more suitable:

$$\ln\left(ROP\sqrt{\frac{\gamma}{UCS}}\right) = A\ln(\alpha) + B\ln\left(\frac{UCS \times DPW}{PSI}\right) + C\ln\left(\frac{BTS}{UCS}\right) + D \quad (9)$$

Eq. 10 was obtained by the simplification of Eq. 9:

$$ROP = \sqrt{\frac{UCS}{\gamma}} \times \alpha^{A} \times \left(\frac{UCS \times DPW}{PSI}\right)^{B} \times \left(\frac{BTS}{UCS}\right)^{C} \times e^{D} \quad (10)$$

These formulas showed that UCS and PSI from the intact rock characteristics, and DPW and γ from the rock mass characteristics, as the sensitivity analysis, played a very important role in predicting ROP. The unknown coefficients were calculated by SPSS 20. Finally, the relationship between the input parameters and TBM penetration rate could be given as Eq. 11:

$$ROP = 0.006\alpha + 0.032PSI - 0.002D - 0.003UCS - 0.007BTS - 0.202DPW + 1.429 \quad (11)$$

Root mean square error (RMSE) of Eq. 11 was 0.29. Also the correlation coefficient obtained for this equation was 0.81, which was comparable with the correlation coefficient obtained by Yagiz (r = 0.82) [27].

According to the amount of correlation coefficient of this equation, it can be concluded that the presented relationship can estimate the penetration rate of TBM correctly.

In order to validate the suggested equation, 20 percent of datasets were selected randomly. A graphic comparison of the measured and predicted ROP is shown in Figure 4. As seen in this figure, a very high conformity exists between the measured and predicted ROP. Also a correlation between the measured and predicted ROP is shown in Figure 5. In this figure, it can be seen that the correlation coefficient is high.

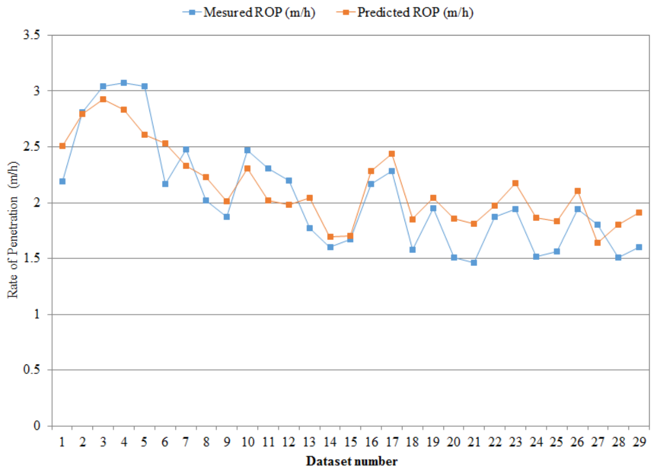

Figure 4. Comparison between measured and predicted ROP.

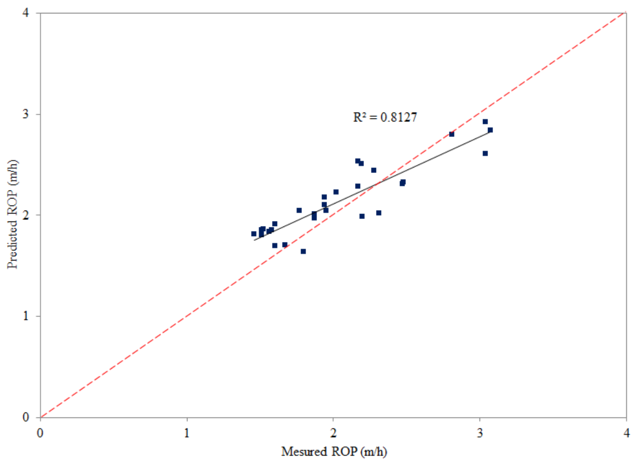

Figure 5. Correlation between measured and predicted ROP.

3.3. Simulating TBM penetration rate

For determining the probability distribution function of the TBM penetration rate, it was necessary to initially calculate the distribution functions of all the input parameters. For this purpose, @risk version 6 was used. Table 4 shows the most appropriate distribution functions of the input parameters.

The probability distribution function of the TBM penetration rate could be calculated by locating the distribution functions obtained (Table 4 and Eq. 11) and using the MC simulation (Figure 6). According to Figure 6, the average penetration rate of TBM in the mentioned tunnel was approximately 2.1 m/h.

Table 4. Probability distribution functions of input parameters.

Parameter	Distribution function
UCS	Weibull (1.4492,35.47)
BTS	Weibull (8.5514,6.522)
Density	Loglogistic (2,0.78575,7.2348)
PSI	Invgauss (11.343,18.569)
DPW	Uniform (0.037171,2.0128)
α	BetaGeneral (1.1591,1.211,1.7662,89.412)

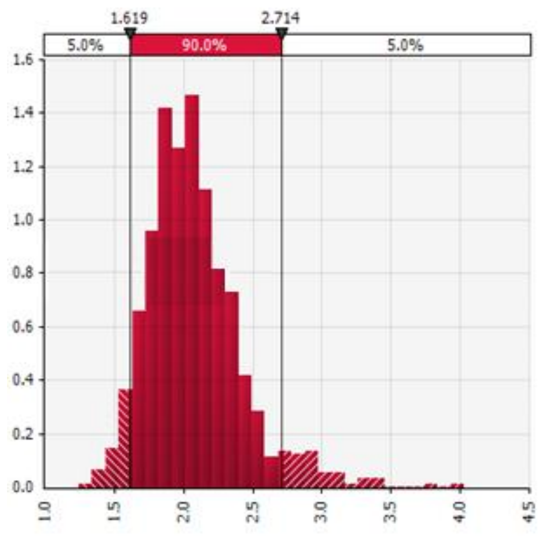

Figure 6. Probability distribution function of TBM penetration rate.

4. Discussion

In comparison with the statistical methods, the mentioned distribution function gave a better view for the penetration rate changes, and instead of a number, it could give a range of changes in ROP. For example, with a confidence level of 90%, the TBM penetration rate in the mentioned tunnel was between 1.59 and 2.71 m/h. The value for ROP in several confidence levels are shown in Table 5. The average measured ROP was about 2.04 m/h, which was less than the confidence level of 50%. This meant that ROP in 57 percent of the cases was less than half. On the other hand, ROP in only 7 percent of the cases was more than the confidence level of 90%.

Table 5. ROP value in several confidence levels.

Row	Percentile	ROP (m/h)
1	5%	1.59
2	10%	1.68
3	50%	2.1
4	90%	2.51

Sensitivity analysis was performed on the input parameters (Figure 7), and it was found that hardness and density had the most and least effects on the TBM penetration rate, respectively.

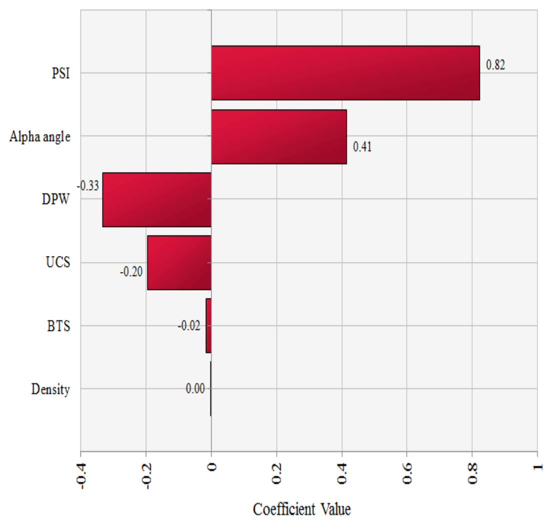

Figure 7. Sensitivity analysis of input parameters.

5. Conclusions

In this study, an attempt was made to investigate the effects of rock mechanic parameters on the TBM penetration rate using the two diverse approaches dimensional analysis and Monte-Carlo (MC) simulation. The following results were obtained:

- Dimensional analysis can be used as a reliable and efficient tool for solving the rock mechanics problems.
- Based on the rock mechanics parameters, a new mathematical equation was presented for calculating the TBM penetration rate. The RMSE error of the equation obtained was less than 0.3.

- MC simulation can be used as an efficient technique for the prediction of the TBM penetration rate.
- The sensitivity analysis shows that hardness and density of rocks have the most and least effects on the TBM penetration rate, respectively.

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تخمین نرخ نفوذ ماشین‌های حفر تونل با استفاده از روش شبیه‌سازی مونت‌کارلو

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چکیده:

یکی از مهم‌ترین پارامترهای تعیین‌کننده عملکرد ماشین‌های حفر تونل (TBMs)، شاخص نرخ نفوذ است. پارامترهای تأثیرگذار بر شاخص نرخ نفوذ را می‌توان به دو دسته قابل‌کنترل نظیر مشخصات فنی TBM، نوع و هندسه تونل و غیرقابل‌کنترل شامل خصوصیات سنگ بکر و مشخصات ناپیوستگی‌های توده سنگ تقسیم‌بندی کرد. هدف از انجام این تحقیق، بررسی آثار خصوصیات توده سنگ بر شاخص نرخ نفوذ و ارائه یک رابطه ریاضیاتی جدید به روش آماری برای برآورد عملکرد TBM است. به‌منظور دست‌یابی به این هدف، از روش شبیه‌سازی مونت‌کارلو برای مدل‌سازی عملکرد TBM استفاده شد. بر این اساس ابتدا پایگاه داده‌ای متشکل از اطلاعات مکانیک سنگی شامل مقاومت فشاری تک‌محوره، مقاومت کششی برزیلی، سختی و سفتی سنگ، فاصله‌داری و جهت‌داری ناپیوستگی‌ها و نرخ نفوذ اندازه‌گیری شده TBM در ۱۵۱ نقطه از یک تونل انتقال آب تشکیل شد. سپس با استفاده از روش آنالیز ابعادی یک رابطه ریاضیاتی جامع برای محاسبه میزان نرخ نفوذ TBM بر اساس داده‌های یادشده توسعه داده شد. درنهایت با استفاده از روش شبیه‌سازی مونت‌کارلو تابع احتمالاتی شاخص نرخ نفوذ مورد بررسی قرار گرفت. نتایج اعتبارسنجی نشان داد که مجذور مربعات خطای (RMSE) رابطه پیشنهادی کمتر از ۰/۳ است. نتایج شبیه‌سازی مونت‌کارلو نشان داد که سختی و چگالی سنگ به ترتیب بیشترین و کمترین تأثیر را بر روی نرخ نفوذ TBM دارند.

کلمات کلیدی: ماشین حفر تونل، نرخ نفوذ، شبیه‌سازی مونت‌کارلو، آنالیز ابعادی.
