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Prediction of TBM performance based on specific energy

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Abstract. This study proposes a new empirical model to effectively predict the excavation performance of a shield tunnel boring machine (TBM). The TBM performance is affected by the geological and geotechnical characteristics as well as the machine parameters of TBM. Field penetration index (FPI) is correlated with rock mass parameters to analyze the effective geotechnical parameters influencing the TBM performance. The result shows that RMR has a more dominant impact on the TBM performance than UCS and RQD. RMR also shows a significant relationship with the specific energy, which is defined as the energy required for excavating the unit volume of rock. Therefore, the specific energy can be used as an indicator of the mechanical efficiency of TBM. Based on these relationships with RMR, this study suggests an empirical performance prediction model to predict FPI, which can be derived from the correlation between the specific energy and RMR.

Keywords: TBM performance prediction; FPI; specific energy; RMR; regression analysis

1. Introduction

Three decades have passed since the first electrical power tunnel in South Korea was constructed using tunnel boring machine (TBM). TBM tunneling is widely used nowadays to excavate electrical power tunnels for laying electrical power lines in the ground. The number of electrical power tunnels has been constantly increased to resolve social issues such as natural landscape preservation and negative perception of electrical power facilities. Tunneling conditions of excavated tunnels have recently diversified because they had lengths generally greater than a few kilometers and an excavation depth of more than 50 m. An accurate prediction of the TBM excavation performance is more important for the selection of the most suitable TBM machine or excavation technology, which are directly related to construction schedule and cost. The TBM performance is affected by the geological and geotechnical characteristics as well as the machine parameters of TBM. Furthermore, the mechanical performance prediction of the TBM machine is significantly influenced by the quality of the database collected from the ground investigation performed before the TBM excavation.

Many researchers developed a number of prediction models to estimate the TBM performance or net penetration rate. CSM (Colorado School of Mines) (Rostami and Ozdemir 1993, Rostami 1997), NTNU (Norwegian University of Science and Technology) (Blindheim 1979, Bruland 1998) and KICT-SNU (Korea Institute of Construction Technology-Seoul National University) (Chang *et al.* 2006a, b) models are the most widely recognized models in the world.

The CSM model developed by EMI (Earth Mechanics Institute of Colorado School of Mines) was based on the individual cutter forces and penetration depth obtained from a laboratory test on intact rock performed using LCM (linear cutting machine) to assess the TBM performance prediction. The shortcomings of the CSM model are that obtaining intact rock blocks is difficult for the LCM test in the field and not definitively explained for the experimental methods and the procedure measuring effective parameters.

The NTNU model is a comprehensive empirical model considering intact rock and rock mass as well as machine parameters to estimate the penetration rate. However, special and empirical laboratory tests for measuring the indices (i.e., drilling rate index, brittleness index, and cutter life index) must be performed for the application of this model. Although the KICT-SNU model is a TBM performance prediction model integrating the advantages of CSM and NTNU models, it still has some of the limitations exhibited by these models. Yagiz (2002, 2008) improved the CSM model to account for the rock mass properties as the input parameters. However, this model also had limitations similar to those of the CSM model.

Other empirical prediction models for accounting for a wide range of rock properties and rock mass conditions have been developed as well. Barton (1999, 2000) developed a model to predict the TBM penetration rate

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using a modified Q-system with RQD (rock quality designation), joint spacing, and thrust. However, the input parameters used in this model were complicated to apply in practice. Farrokh *et al.* (2012) proposed the models improving the accuracy of the commonly used TBM performance prediction models. These models are based on the analysis of a comprehensive database including the TBM diameter and the rock type. Benato and Oreste (2015) introduced the empirical formulation considering both the intact rock (i.e., UCS) and rock mass characteristics (i.e., GSI). Some of the TBM performance prediction models required the specific rock mass characteristics (e.g., PSI, BI, DPW, J_v, and α) to the estimation of penetration rate (PR) (Yagiz, 2008; Minh *et al.* 2017).

Gong and Zhao (2009) introduced a statistical prediction model with respect to the boreability index (BI). BI is a comprehensive parameter related to the rock mass properties, the TBM machine specification, and the operation factors. There are also researches employing FPI, which have semantic meaning with BI. Hassanpour *et al.* (2011) developed an empirical prediction model based on two main properties (i.e., UCS and RQD) to obtain FPI as a TBM performance parameter. Mobarral *et al.* (2013) analyzed the relationship between FPI and rock mass properties and found that FPI is more closely related to the rock mass characteristics than PR. Salimi *et al.* (2016) showed a significant relationship between FPI and UCS. Lee *et al.* (2017) also analyzed the correlation between FPI and other influencing parameters (i.e., UCS, RMR, L_v) using the regression analysis. Some authors considered blocky rock conditions that influence negatively overall TBM performance. They applied FPI_{blocky}, which is defined as the ratio between the TBM total thrust force and PR, to estimate the TBM performance in blocky rock conditions (Delisio *et al.*2013; Delisio and Zhao, 2014).

Although wide variety of performance prediction models and principles have been developed and applied to estimate the TBM performance, the care must be taken when applying those models. Hassanpour *et al.* (2016) indicated the importance of the application range of the model and geological conditions that the original model is based on.

On the other hand, concept of specific energy has been used to predict the optimized field performance of the TBM excavation. The specific energy is the energy required to excavate the unit volume of rock mass. Teale (1965) first introduced the concept of specific energy to determine the drilling efficiency of a rotary drilling bit in the petroleum industry. Since the cutting mechanism of the cutter head of TBM was similar to that of the rotary drilling bit, many researches has been carried out using specific energy to predict the TBM performance (Celada *et al.* 2009; Bieniawski *et al.* 2012). Celada *et al.* (2009) and Bieniawski *et al.* (2012) analyzed the correlations between the specific energy and FPI or RMR (rock mass rating) using the data obtained from the Guadarrama Tunnel and the San Pedro Tunnel sites. They used these correlations to detect any significant change in the rock mass quality and the excavation efficiency in real-time.

In South Korea, researches to predict the TBM performance using specific energy is insufficient due to the lack of available data obtained during the TBM excavation and the difficulty of access to the information on the excavation site and TBM machine.

The main objective of this study is to suggest an empirical prediction model of TBM performance by analyzing the correlation of field geotechnical and performance data. Since the analyzed field data, such as UCS, RQD, RMR and penetration depth, were collected from the TBM excavation site of a small shield TBM with 3.3 m diameter in South Korea, regional characteristics should be well reflected. Correlations were analyzed by the regression analysis. The regression analysis is widely used to evaluate the correlation of the geotechnical behavior and performance by many researchers (Zhang *et al.* 2015, Salimi *et al.* 2016, Zhou *et al.* 2016). FPI was adopted as a parameter for assessing the TBM performance and correlation analysis with the specific energy calculated using the field data was conducted.

2. Theoretical background

2.1 Specific energy

Specific energy, which is defined in Eq. (1), is the energy required to excavate the unit volume of rock mass. This type of energy is regarded as the index for assessing the machine efficiency and the geological and geotechnical properties of rock mass (Teale 1965).

$$SE = \frac{F}{A} + \frac{2\pi\omega T}{Au} \tag{1}$$

where SE is the specific energy (kWh/m^3 or MJ/m^3), F is thrust (kN), A is cutting area (m^2), ω is rotation rate (RPS, rev/s), T is torque (kN-m), and u is penetration rate (m/s).

The specific energy consists of two parts: 1) thrust and 2) rotation parts. The researches by Teale (1965) indicates that the specific energy related to the thrust account only for 2% of the total energy; thus, this part can be neglected. The specific energy can be redefined as Eq. (2).

$$SE \approx \frac{2\pi\omega T}{Au} \tag{2}$$

2.2 Field Penetration Index (FPI)

Data (e.g., RPM, thrust, and penetration depth) were automatically recorded in the black box of the TBM machine during the TBM excavation. The parameters related to the TBM performance prediction can be derived from the data shown in Eqs. (3)-(5).

$$ROP = \frac{L}{t} \tag{3}$$

$$P_e = \frac{ROP \times 1{,}000}{RPM \times 60} \tag{4}$$

$$FPI = \frac{F_n}{P_e} \tag{5}$$

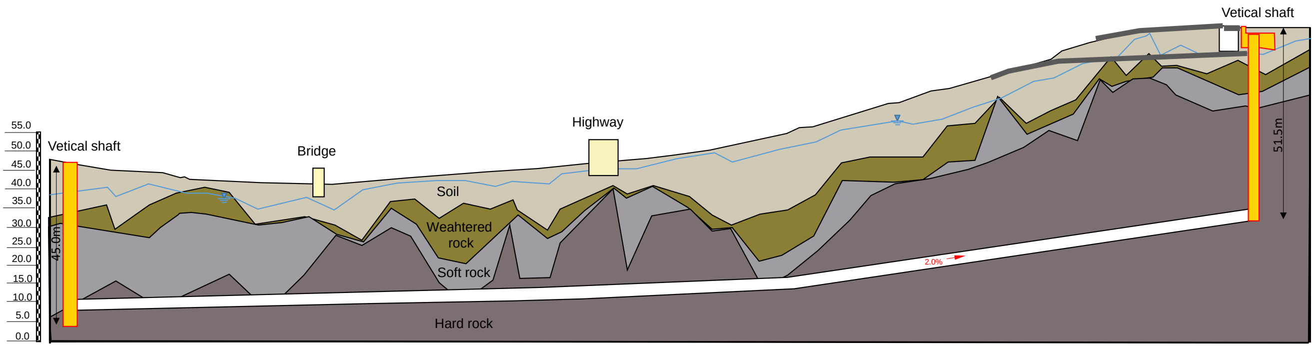

Fig. 1 Horizontal tunnel section

Table 1 Tunnel project profile

Project	○○ electric power tunnel	Tunnel Length	2,258 m
TBM type	Single EPB	Manufacturer	Kawasaki(2013)
O.D	3,330 mm	Radius of curvature	120 m
Max RPM	9.0 rev/min	Max stroke	1,750 mm
Max Torque	1,250 (Norm.550) kN·m	Thrust per jack	800 kN
Cutter type	CCS (14 inch)	Total thrust	9,600 kN
Cutter No.	26EA	Power	680 kW

Table 2 Rock mass profile

Sort	UCS (MPa)	RQD (%)	RMR	Deformation Modulus (GPa)	Quartz content (%)	Poisson's ratio
Min	22.0	10.0	49.0	17.2	25.6	0.18
Max	97.3	100.0	84.0	67.0	35.0	0.28
Mean	53.9	72.1	67.0	41.0	30.3	0.23
Std. dev	22.1	23.5	9.4	18.2	-	-

where *ROP* is net penetration rate (m/hr), *L* is segment length (m), *t* is net penetration time per segment(hr), *RPM* is speed (rev/min). F_n is cutter thrust (kN), P_e is penetration depth (mm).

3. Project description

The field data were obtained from the TBM excavation site of the electric power tunnel in Gunpo, South Korea. The TBM machine applied for the excavation was on earth pressure balance (EPB) type single shield TBM with an outer diameter of 3.3 m and manufactured by Kawasaki heavy industries in 2013. Table 1 summarizes the TBM machine specifications.

The field data was collected from an approximate length of 2,050 m, which corresponded to 90 % of the total tunnel length. The depths of the shafts for carrying the TBM machine in and out were 45 m and 51.5 m, respectively. The horizontal route of the tunnel penetrated the ground, where UCS ranged from 22 MPa to 97 MPa (Fig. 1).

The geological formations were identified as Precambrian biotite banded gneiss and some intrusive rocks. Table 2 lists the intact rock and rock mass properties analyzed by laboratory and field tests.

4. Field database analysis

The database was built using the field data obtained from the ground investigation and the automatically recorded machine data to analyse the correlation between the effective parameters and the specific energy. The machine data was compiled with reference to the borehole location. As a result, the 28 data were selected to analyse the TBM performance.

The values of the performance parameters (i.e., ROP, PR, FPI, and specific energy) were calculated using the operation parameters (e.g., thrust, torque, RPM, and power) recorded in the TBM machine. The graphs in Fig. 2 represent the histogram and the distribution curves of UCS, RQD, PR, and FPI. UCS and RQD values were in the 53.9 ± 22.1 MPa and 72.1 ± 23.5 % range, respectively. PR showed values of 26.2 ± 8.9 mm/min, whereas FPI exhibited values widely ranging from 9.5 to 68.7 kN/cutter/mm/rev. These results indirectly indicated that the values varied with the ground conditions.

FPI was correlated with the geological and performance parameters (Fig. 3). The analysis results produced by Hassanpour (2011) were superimposed on Fig. 3 in order to compare the results obtained from this study. In Fig. 3(a), FPI showed a little correlation with UCS because UCS values used in the analysis were narrowly distributed to values of 100 MPa or less, which only corresponded to weathered rock and soft rock. The absence of high UCS values (>100 MPa), corresponding to the hard rock, in the database inferences with the development of a more comprehensive prediction model covering a wide range of ground conditions. As a basis for this assumption, the result studied by Hassanpour *et al.* (2011) showed the best correlation between FPI and UCS, where UCS values ranged widely from 30 MPa to 225 MPa. Meanwhile, FPI was closely correlated with RQD and RMR.

The regression coefficient (R2) between FPI and RQD represented 0.688. This R2 value was similar to that of the distribution suggested by Hassanpour (Fig. 3(b)). R2 between FPI and RMR was 0.864 (Fig. 3(c)), which shows that RMR has the highest correlation with FPI among parameters considered in this study. Table 3 summarizes the

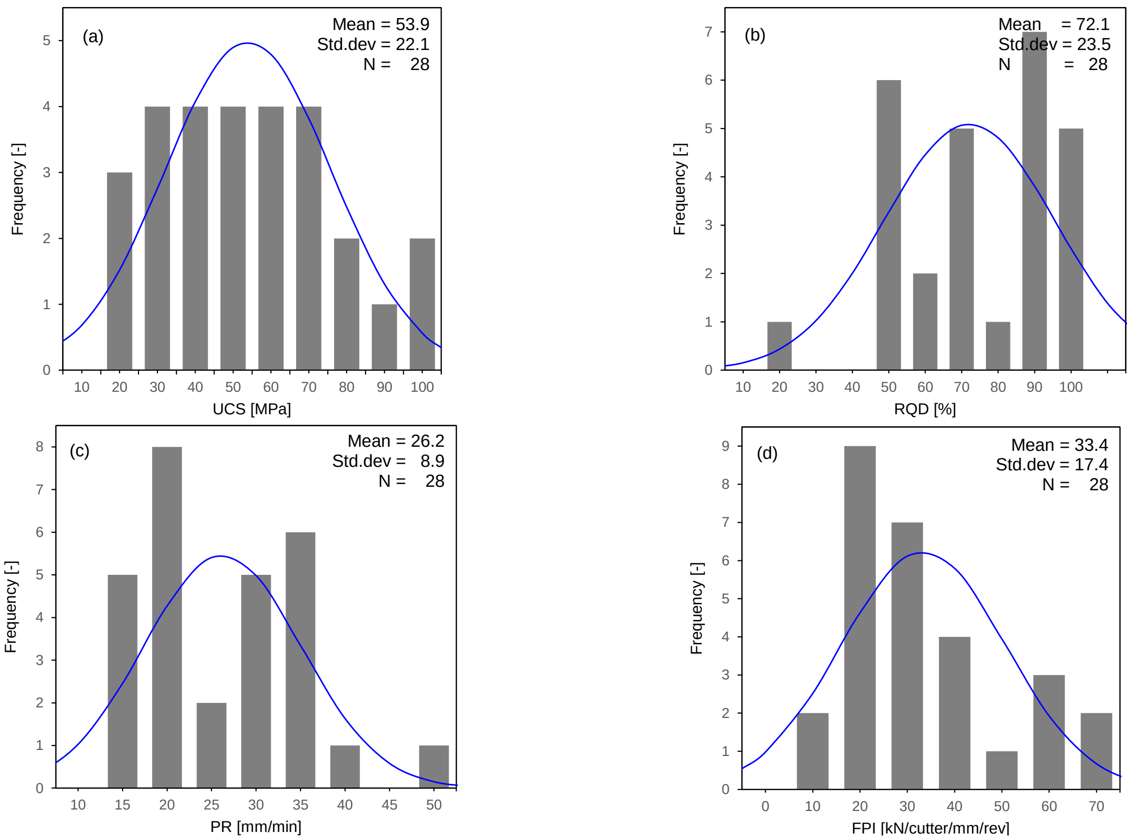

Fig. 2 Histograms of the geological and TBM performance parameters: (a) UCS, (b) RQD, (c) PR and (d) FPI

Table 3 Summary of regression coefficients with FPI

Parameters	Data source	Regression coefficient (R^2)	Regression type	Relationship
UCS (MPa)	Field data	-	Exponential	FPI=16.88EXP(0.013UCS)
	Hassanpour *et al.* (2011)	0.699	Exponential	FPI=6.883EXP(0.013UCS)
RQD	Field	0.688	Exponential	FPI=3.490EXP(0.027RQD)
	Hassanpour *et al.* (2011)	0.688	Exponential	FPI=3.490EXP(0.027RQD)
RMR	Field	0.863	Exponential	FPI=2.5287EXP(0.0357RMR)
	Hassanpour *et al.* (2011)	0.531	Quadratic	FPI=0.053RMR^2-4.205RMR+92.068

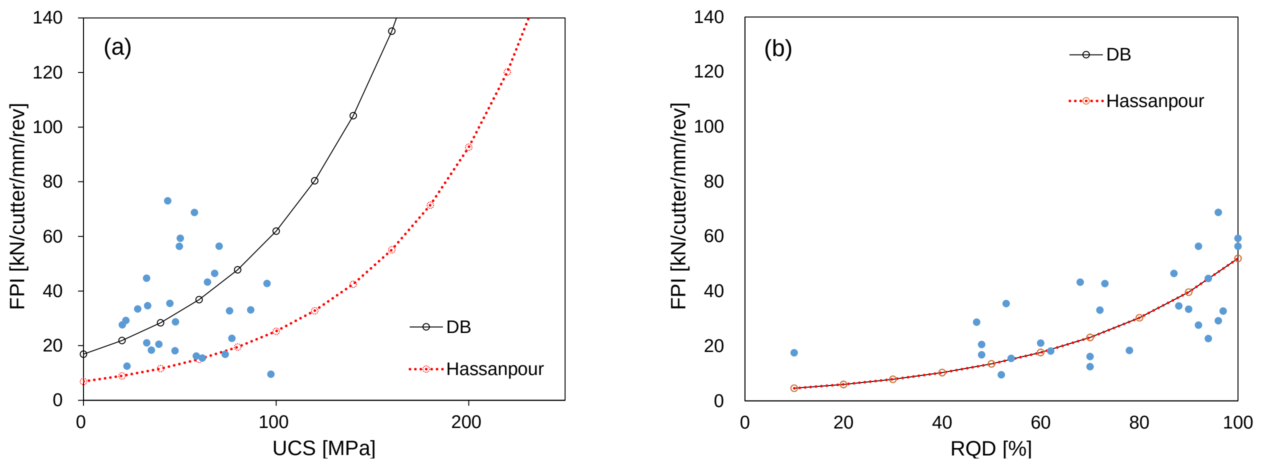

Fig. 3 Correlation between different rock mass properties and FPI: (a) FPI vs. UCS, (b) FPI vs. RQD and (c) FPI vs. RMR

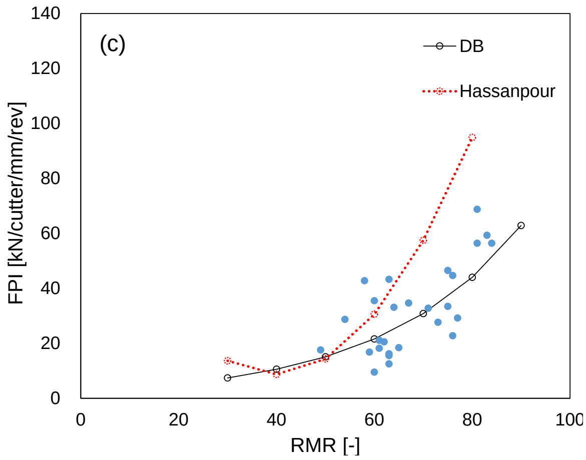

Fig. 3 Continued

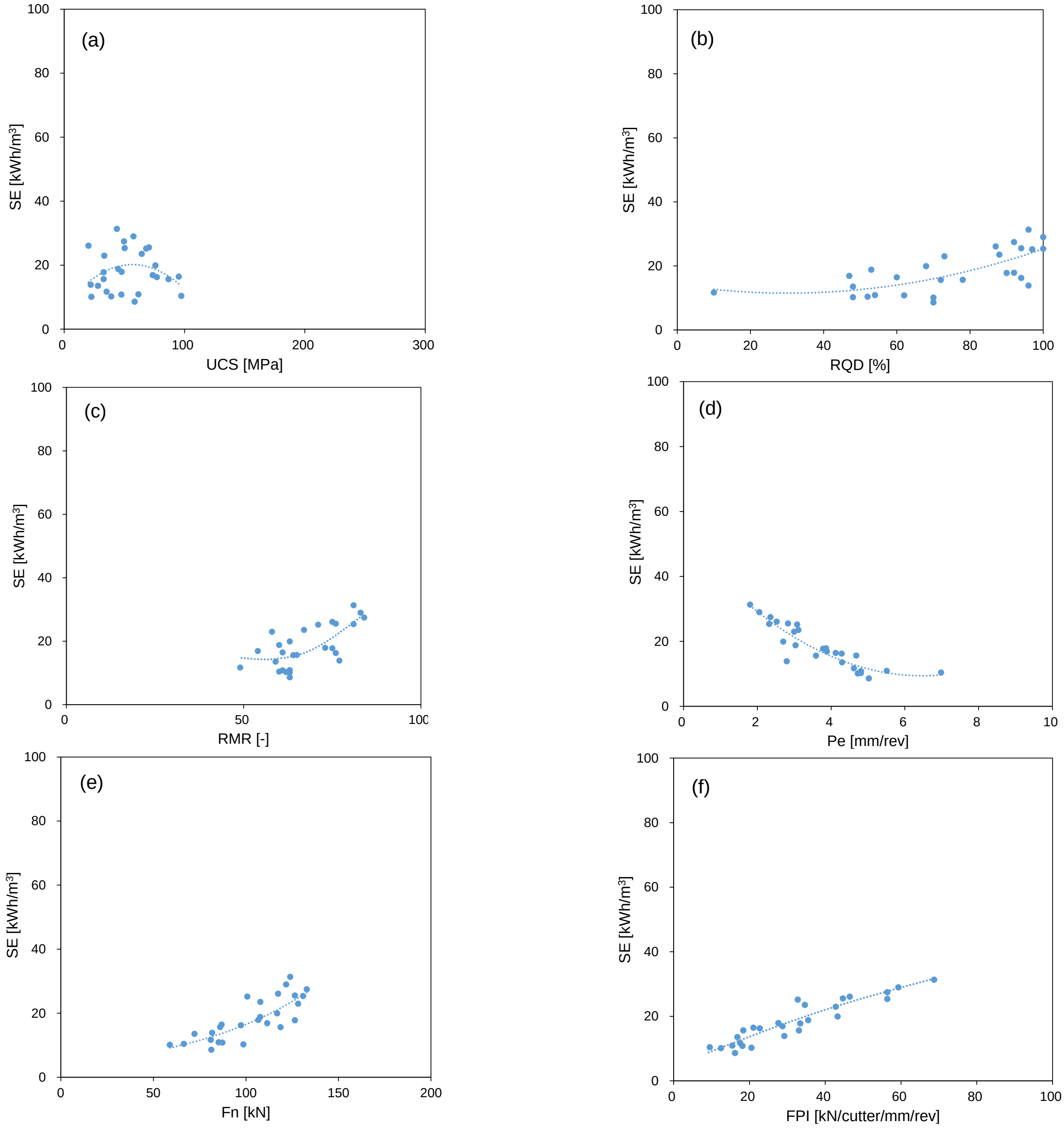

Fig. 4 Correlation between different parameters and the specific energy: (a) specific energy vs. UCS, (b) specific energy vs. RQD, (c) specific energy vs. RMR, (d) specific energy vs. P_e, (e) specific energy vs. F_n and (f) specific energy vs. FPI

Table 4 Summary of regression coefficients with specific energy

Parameters	Regression coefficient (R^2)	Regression type	Relationship
UCS(MPa)	0.093	Quadratic	SE= -0.0041UCS^2+0.4607UCS+7.1152
RQD	0.505	Quadratic	SE=0.0028RQD^2-0.1719RQD+14.109
RMR	0.506	Quadratic	SE=0.01733RMR^2-1.8952RMR+65.668
Pe	0.835	Quadratic	SE=0.9918Pe^2-12.821Pe+50.845
Fn	0.664	Exponential	SE=3.9183EXP(0.0144Fn)
FPI	0.865	Quadratic	SE=-0.0019FPI^2+0.524FPI+3.8364

Table 5 Summary of the regression coefficient with the specific energy considering the San Pedro Tunnel

Parameter	Regression coefficient (R^2)	Regression type	Relationship
RMR	0.864	Exponential	SE=0.511EXP(0.0506RMR)

empirical equations derived from the relationship between FPI and the major geological and performance parameters.

The specific energy defined as the energy for excavating the unit volume of rock is a useful parameter to be taken as an index of the mechanical efficiency of a rock excavation process (Celada 2009). Regression analyses were performed to assess the mechanical efficiency of the TBM machine using the collected database. In Fig. 4(a), the specific energy and UCS showed a weak correlation, which resulted from the 50 resulted in the low regression coefficient for the correlation between RMR and the specific energy. The specific energy and the penetration depth, which was the depth of the cutter head penetration into the ground, showed a close correlation with an R^2 of 0.835 (Fig. 4(d)). Moreover, FPI was correlated with the specific energy. The result represented in Fig. 4(f) showed a high correlation between the two performance parameters with R^2 of 0.865.

The specific energy defined as the energy for excavating the unit volume of rock is a useful parameter to be taken as an index of the mechanical efficiency of a rock excavation process (Celada 2009). Regression analyses were performed to assess the mechanical efficiency of the TBM machine using the collected database. In Fig. 4(a), the specific energy and UCS showed a weak correlation, which resulted from the same reason to be represented in the relationship analysis between FPI and UCS. The R^2 of the specific energy correlated with RQD and RMR were 0.505 and 0.506, respectively (Figs. 4(b) and 4(c)). The low R^2 values for the correlation of the specific energy and RMR may be caused by the unbalanced distribution of the RMR values being concentrated at the values ranging from 49 to 84. In other words, it supposed that the lack of lower RMR values than 50 resulted in the low regression coefficient for the correlation between RMR and the specific energy. The specific energy and the penetration depth, which was the depth of the cutter head penetration into the ground, showed a close correlation with an R^2 of 0.835 (Fig. 4(d)). Moreover, FPI was correlated with the specific energy. The result represented in Fig. 4(f) showed a high correlation between the two performance parameters with R^2 of 0.865. Table 4 summarizes the regression analysis results for correlating the specific energy with the major geological and performance parameters.

An additional analysis was performed using a supplemented RMR database because the correlation coefficient (R^2) between the specific energy and RMR shows a somewhat low value different from that of FPI and RMR. A total of 80 geological and performance data for the San Pedro Tunnel site were extracted from the study by Celada. The data included in the database corresponded to RMR values lower than 50. The regression analysis using 108 data (i.e., 28 data from the Gunpo Electric Power Tunnel and 80 data from the San Petro Tunnel) resulted in R^2 increased to 0.864, which was 70% higher than 0.506 derived from the analysis using only the 28 data collected from the Gunpo tunnel (Fig. 5 and Table 5).

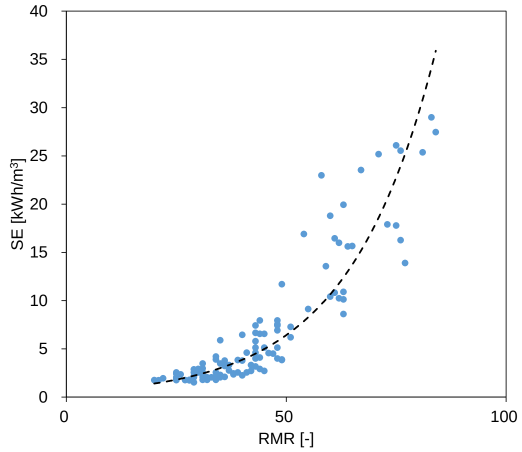

Fig. 5 Correlation between the RMR and the specific energy using the supplemented RMR database

5. Developing empirical equation

As indicated in the abovementioned analyses, FPI, as an index of the TBM performance, was strongly correlated with RMR and the specific energy showing R^2 of 0.864 and 0.865, respectively. The following empirical equation (i.e., Eq. (6)) was introduced as a function of the specific energy based on the correlation with RMR to predict the TBM performance.

$$FPI = 0.0471(SE)^2 + 0.4004(SE) + 6.9643 \quad (6)$$

where SE is the specific energy (kWh/m^3 or MJ/m^3).

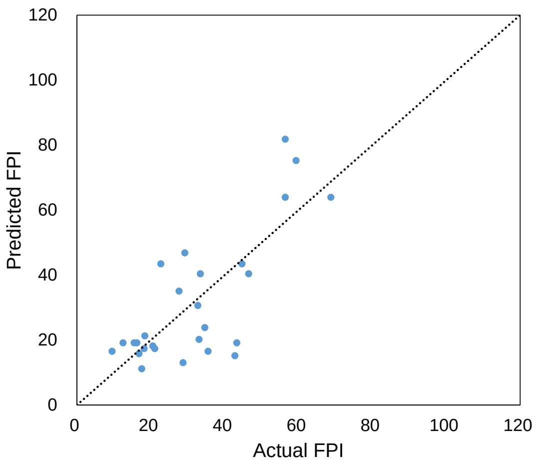

Fig. 6 Comparison of the actual and predicted FPI

Fig. 6 shows the graph for comparing the actual and predicted FPI value. The actual FPI were calculated using Eq. (5). Most of the predicted FPI values were close to the actual FPI values with only 1.5% of the averaged error rate. Therefore, it indicated that the proposed empirical equation can predict the TBM performance using only the specific energy which can be calculated from the correlation with RMR using Table 5. Moreover, it can be useful for managing the mechanical efficiency of TBM through the real-time comparison of the expected FPI and calculated FPI using recorded data in the site.

6. Conclusions

This study introduced an empirical equation for predicting the TBM performance using the statistical approach. The rock mass properties (i.e., UCS, RQD, and RMR) and the performance parameters (i.e., PR and FPI) were analyzed to estimate the TBM performance. FPI was calculated as a TBM performance parameter from the correlation with the specific energy. The specific energy was obtained from the correlation with RMR. The results of this study are summarized as follows.

- FPI was correlated with various rock mass properties to identify the effective parameters on the TBM performance. As a result, RMR showed a good correlation with FPI than with UCS or RQD.
- The specific energy defined as the energy for excavating the unit volume of rocks was very closely related to RMR (Table 5). Moreover, the specific energy calculated from RMR was verified as a useful parameter to predict the TBM performance because it was significantly related with FPI.
- The Predicted FPI calculated from the proposed model was compared with the actual FPI. The reasonable correlation between the predicted and actual FPI was achieved with the correlation coefficient of 0.865. Therefore, the TBM performance can be predicted using this relationship at the pre-construction phase of TBM tunneling.
- Although a meaningful empirical model was derived from this study, further study may be essential in order to apply this model in practice. One of issues to be considered is that the database should be expanded to supplement the biased distribution of effective parameters, for improving the model for the general application. In addition, reliability of the model should be verified by applying it to various site and ground conditions.

Acknowledgments

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