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Prediction Method of the Boreability and Performance for Hard Rock TBM Tunnel

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Abstract. TBM boreability and performance prediction has always been a hot research topic. In this paper, taking one large diameter long tunnel excavated by a gripper hard rock TBM in Northeastern China as research background, based on a large number of boring data on site and mono-factorial regression analysis of the correlations among Field Penetration Index (FPI) and geological parameters, a multi-factorial regression correlation formula of FPI with rock uniaxial compressive strength (UCS) and rock mass integrity coefficient (*Kv*) was established. Furthermore, the regression correlation formula of TBM penetration (P) with FPI and the formula of thrust (F) with FPI were given. And a classification method of TBM tunnel surrounding rock based on FPI was proposed. Therefore, according to the above formulae, the analysis of boreability, the calculations of TBM penetration, advance rate and the required thrust, and the classification of rock mass can be performed, which provide a theoretical method for the estimation of TBM boreability, performance prediction, specifications design as well as the project planning and duration-cost analysis.

Keywords. Hard rock TBM, boreability, performance, rock classification

1. Introduction

As more and more long tunnels need to be constructed in railway, highway, water conservancy, hydropower and other industries, full face hard rock tunnel boring machine (TBM) has gradually become the first choice due to the consideration of construction period, environmental protection, special topography and other factors. The evaluation of TBM tunneling speed and construction risk can influence the prediction of time limit and cost and the success of the engineering. Therefore, the study of rock mass boreability and tunneling performance has been an important topic in TBM field [1-16]. However, from the perspective of prediction models proposed, some of them rely too much on theoretical calculation and laboratory data, and some have a complex modeling with too many geological factors and TBM design

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parameters, resulting in the absence of practicability and sometimes a big gap with the actual results.

In fact, first, the geology is hard to describe precisely. Secondly, with the development of TBM design performance, the adjustable limit of the tunneling parameters is enlarged. In some rock conditions, the design parameters exceed the actual needs, which makes it easy to achieve the desired penetration. Also, some geological parameters have little influence compared with the main parameters, as well as strong correlations among them. Thirdly, the TBM performance from different manufacturers and the operating parameters of different operators may be quite different. Therefore, the influence of above factors is far beyond some minor geological factors in the model. Considering the design of TBM, excluding the geological factors with less influence or collinear problems and grasping the key geological factors, the analysis and model are carried out by massive tunneling data of different surrounding rocks from actual engineering cases. And more reliable and practical prediction models are expected to be proposed. The case study presented here, based on an 8.5 m diameter tunnel with the giant porphyritic granite excavated by TBM, will be part of this attempt.

2. TBM Technical Parameters and Rock Performance Test

This study is based on an extra-long tunnel in Northeast China, which adopts open-type TBM with 8.5m boring diameter. And the lithology is giant porphyritic granite. Main technical parameters of TBM are shown in table 1.

To analyze the correlation between the TBM tunneling performance and rock mass parameters, the uniaxial compressive strength (UCS) and abrasion of rock samples were tested in the Laboratory of Rock Mechanics, Chinese Academy of Sciences.

The rock samples were made into cylinders with a diameter of 40~50 mm and a height of 90~100 mm. The rock uniaxial compressive strength test was carried out by TAW-2000 microcomputer controlled electro-hydraulic servo rock triaxial testing machine. ATA-IGG I rock Attrition servo test device was used to test the value of the CERCHAR Abrasiveness Index (CAI).

Table 2 lists the test results of UCS and CAI. It can be seen that the uniaxial compressive strength of the giant porphyry granite in this project is about 80~175MPa, and the abrasion value is about 5~9, which is a hard rock with extremely abrasive.

Table 1. TBM Specifications.

TBM technical parameter	Design value
Number of center cutters (diameter/mm)	8/432
Number of face cutters (diameter/mm)	35/508
Number of gage cutters (diameter/mm)	10/508
Rated load of disc cutter (kN)	311.5
Cutterhead driving power (kW)	3300
Cutterhead rotational speed (rpm)	0~7.98
Rated torque (kN·m)	6713
Rated thrust /kN	20491
Maximum driving stroke /mm	1829
Maximum gripping force /kN	45394

Table 2. Rock compressive strength and abrasive index.

Sample number	Height/mm	Diameter/mm	UCS/MPa	CAI/mm
60756-1	91.09	42.90	175.885	85.37
60756-2	90.53	42.91	136.193	58.39
60756-3	90.39	42.75	143.869	
60822-1	90.60	42.99	111.058	85.69
60822-2	91.82	42.99	101.972	
60822-3	90.49	42.96	78.077	
61595-1	92.16	42.54	146.392	88.38
61957-1	91.32	42.72	155.755	
61957-2	90.34	42.58	121.458	65.40
61957-3	90.40	42.49	131.728	
62158-1	90.54	42.80	135.820	55.75
62158-2	91.02	42.71	108.227	
62158-3	90.00	42.85	110.841	
62284-1	90.81	42.87	160.013	59.83
62284-2	90.26	42.77	102.869	66.41
62284-3	91.55	42.86	128.590	68.19
62638-3	89.83	43.24	125.717	76.22

3. Mono-factor Regression Analysis of FPI and Rock Mass Parameters

Formerly the engineering practices and theoretical researches indicated [1,6-14,17-19] that whether rocks are easy to boring can be measured by the ratio of single-cutter thrust to penetration, namely Field Penetration Index (FPI). To predict the value of FPI by the surrounding rock parameters, firstly, this paper analyses the correlation between FPI and rock mass parameters based on driving force and penetration obtained from the site under different rock mass conditions, and determines the key geological parameters that have great influence on FPI.

3.1. Correlation between FPI and UCS

According to the tunneling parameters recorded on site every day, such as the thrust and penetration, EXCEL software is used to perform statistical analysis, calculate the FPI value, draw the scatter plot (figure 1(a)) and then fit the trend of UCS and FPI. The regression equation is:

$$FPI = 5.631e^{0.015\,1UCS} \quad (R^2 = 0.935) \tag{1}$$

As can be seen in figure 1(a), the filed penetration index (FPI) shows good correlation with the uniaxial compressive strength of rock (UCS), indicating that the UCS has a great influence on the FPI and is a key factor affecting the excavation efficiency of TBM.

3.2. Correlation between FPI and Kv

Many researchers have studied the relationship between rock mass integrity and TBM tunneling performance. Through simulation analysis or field practice, it can be shown that rock mass integrity has a great impact on penetration and tunneling speed of TBM [1,5-9,20]. In general, the more complete the rock mass is, the higher thrust will be selected by the TBM operator to obtain the greater penetration. On the contrary, if the rock mass contains many joints and fractures, a greater penetration can be obtained under the lower thrust.

The rock mass integrity coefficient (Kv), given by counting the rock joints, is used to reflect the influence of joints and cracks. Sampling points with the same lithology and uniaxial compressive strength are selected to draw and fit the scatter chart of Kv and FPI (as shown in figure 1(b)). The fitting relation between the FPI and Kv is obtained as follows.

$$FPI = 2.089\ 2e^{3.959K_v} \quad (R^2 = 0.788\ 3) \tag{2}$$

Figure 1(b) shows a good correlation between rock mass integrity coefficient (Kv) and filed penetration index (FPI), which means the FPI is affected by rock mass integrity to a large extent.

3.3. Correlation between FPI and CAI

Similarly, as shown in figure 1(c), the FPI was calculated by the actual driving force and penetration recorded on site, and the fitting formula between FPI and CAI was built as Eq. (3).

$$FPI = 15.303e^{0.226CAI} \quad (R^2 = 0.652\ 3) \tag{3}$$

It follows from the single factor regression analyses above that the correlation coefficient of FPI with UCS, Kv or CAI is greater than 0.6 based on the tunneling parameters and geological parameters on site. And among these geological parameters, the UCS shows the best correlation with FPI, followed by the Kv or CAI.

To comprehensively consider the relationship of FPI and various geological factors, multiple regression analysis is carried out. In this process, the correlation between geological factors is studied to exclude the collinear problems among these factors, thereby eliminating its influence on the results of multiple regression analysis.

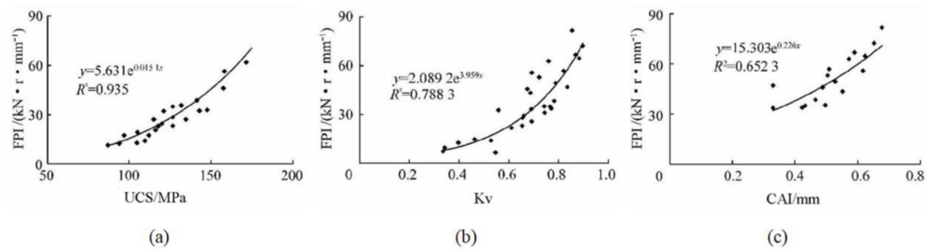


Figure 1. Correlation of FPI and UCS, Kv, CAI.

4. Multiple Regression Analysis of FPI and Rock Mass Parameters

4.1. Correlation between UCS and Kv

Based on the surrounding rock parameters of the support project, the fitting results of UCS and Kv are shown in Eq. (4) and figure 2(a).

$$UCS = 0.003\ 3K_v + 0.388\ 1 \quad (R^2 = 0.331\ 6) \tag{4}$$

4.2. Correlation between UCS and CAI

As shown in figure 2(b), the fitting formula was established by the test results of UCS and CAI as follows.

$$UCS = 19.032CAI + 39.563 \quad (R^2 = 0.685\ 3) \tag{5}$$

4.3. Correlation between Kv and CAI

Similarly, through the regression analysis, using the data of Kv and CAI from field monitoring, the formula was fitted out as Eq. (6) and figure 2(c).

$$CAI = 83.915K_v^2 - 126.4K_v + 52.298 \ (R^2 = 0.286\ 1) \tag{6}$$

As mentioned above, the uniaxial compressive strength of rock (UCS) is highly correlated with CERCHAR Abrasiveness Index (CAI), which is a collinear problem. The correlation between the rock mass integrity coefficient (Kv) and UCS or CAI is not obvious. In addition, from the above analysis, the correlation coefficient (R^2) between UCS and FPI is 0.935, and the correlation coefficient between CAI and FPI is 0.6523. Therefore, excluding the collinear factors, the UCS with a larger correlation coefficient is taken as the factor in the following multiple regression analysis.

Moreover, the geological parameters such as brittleness index and joint orientation also have some effect on rock mass boreability. But for hard rocks, especially the brittleness index in a less variable range, it has little effect when compared with UCS and rock integrity[8]. For soft rocks, the TBM driving parameters used to achieve high penetration are far below the design values. Thus, compared with the effects of the TBM design parameters, compressive strength and integrity of rock mass, other minor geological factors can be excluded.

This paper relies on the project with giant porphyritic granite, which is relatively hard. The strength and the integrity of rock mass are the key elements affecting the boreability and driving performance of TBM. Therefore, excluding the slight or collinear geological factors, multiple regression analysis was used to build an empirical model to relate UCS and Kv as the key parameters, which are easier to obtain from the existing geological survey data or testing in the stages of project planning, preliminary design, bidding and construction. For this purpose, the UCS and Kv were used as independent variables and the recorded FPI was used as dependent variable, through multiple regression analysis to get a simple and practical prediction model of FPI, which meets the requirements of engineering accuracy.

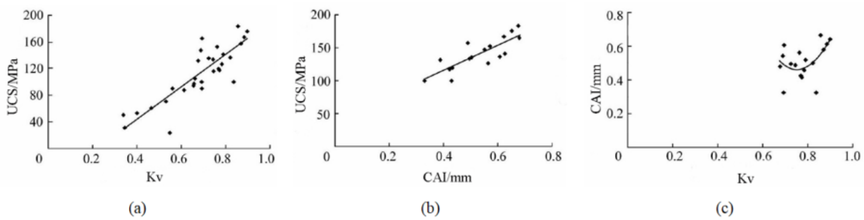


Figure 2. Correlation of UCS, Kv and CAI.

4.4. Multiple Regression Analysis of FPI with UCS and Kv

Using the UCS and Kv as independent variables and the FPI as dependent variable, nonlinear regression analysis was performed by SPSS software based on TBM filed data. The mathematical model is assumed to be $FPI = \exp(a_1 UCS + a_2 K_v + a_3)$, and the unknown variables of a_1, a_2 and a_3 are calculated by iterative method. The initial values of a_1, a_2 and a_3 were set as $a_1 = 0.01$, $a_2 = 0.03$, $a_3 = 2.1$. The constraint conditions were set as $a_1 \geqslant 0$, $a_2 \geqslant 0$, $a_3 \geqslant 0$. After 16 iterations, the estimated values of a_1 , a_2 and a_3 are 0.010, 1.091 and 1.653, respectively. The multiple regression equation of FPI, UCS and Kv can be expressed as follows.

$$FPI = \exp(0.01UCS + 1.091K_v + 1.653) \quad (R^2 = 0.921\,0) \tag{7}$$

In this way, for a TBM project, according to the geological data (UCS and Kv) given in the geological investigation stage, using the Eq. (7) can evaluate the rock mass boreability of different sections, and thereby predict the TBM penetration, advance speed, the time list and cost of the project.

5. Relationship between FPI and TBM Tunneling Performance

5.1. Field Measured FPI and its Distribution

During TBM construction, the data acquisition and record system can record the cutterhead thrust and penetration in real time. Under the condition of giant porphyry granite with different strength and integrity, the FPI value changes within 1882 m, as shown in figure 3.

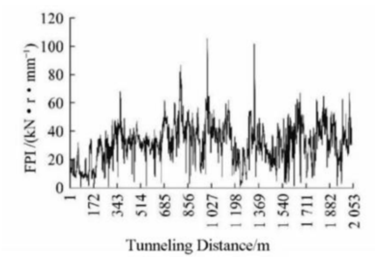


Figure 3. Measured FPI during 1882m advance.

Different FPI values correspond to different thrust and penetration, as well as different rock compressive strength and integrity. The frequency distribution of FPI within 1882m is shown in figure 4.

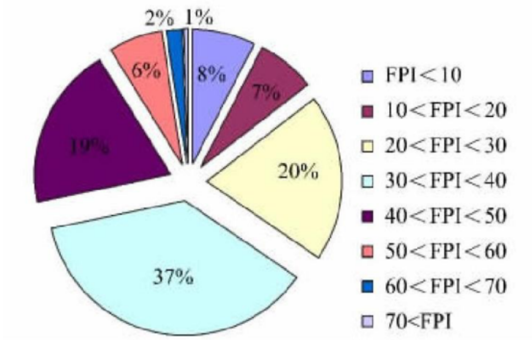


Figure 4. FPI distribution during 1882m advance.

It can be seen from figure 4 that, during 1882m tunneling, different FPI correspond to the different proportion of surrounding rock, among which the surrounding rock with FPI greater than 20 and less than 30 account for 20%; the surrounding rock with FPI greater than 30 and less than 40 accounted for 37%; the surrounding rock with FPI greater than 40 and less than 50 accounted for 19%. In total, the surrounding rocks with FPI greater than 20 and less than 50 accounted for 76%.

If the value of FPI is less than 10, the surrounding rock is weak or overdeveloped joints, which is easy of penetration, but increase the surrounding rock support and TBM trapped risk. A high FPI value, such as more than 60, means that the surrounding rock is hard and intact, making it difficult for the TBM to penetrate. As can be seen from figure 4, most of the sections in this tunnel are easy to be excavated, and the proportion of sections with large support and construction risk is small.

5.2. Relationship between Measured Tunneling Performance and FPI

Table 3 shows the mean values of TBM tunneling parameters (thrust, rotational speed, torque) and performance parameters (penetration, advance speed) corresponding to different values of FPI in actual engineering.

Table 3. Practical FPI corresponding to TBM operating parameters and performance.

FPI	Advance speed (m/h)	Rotational speed (r/min)	Torque (kN·m)	Thrust (kN)	Penetration (mm/r)
FPI <10	3.7	4.3	1710	8562	13.1
10<FPI<20	3.4	5.4	2299	12004	10.0
20< FPI <30	3.2	6.0	2543	14915	8.1
30< FPI< 40	2.9	6.9	2656	17007	7.1
40< FPI <50	2.5	6.5	2399	18109	6.0
50< FPI <60	2.1	6.0	2142	18615	5.1
FPI >60	1.5	5.0	2002	19300	4.2

Obviously, in terms of surrounding rock boreability, to obtain a larger penetration and advance speed, the larger the FPI is, the greater the thrust is needed, and the smaller the FPI is, the smaller the thrust is. However, too small FPI means that the surrounding rock is weak and broken, and the support increase, which delays the downtime of TBM for a long time. Although capable of achieving a larger penetration, the TBM utilization is reduced, leading to a significant decrease in penetration rate.

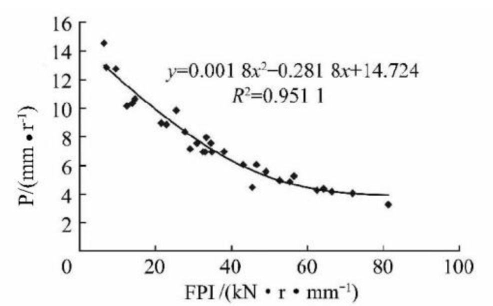
5.3. Fitting Relationship between Penetration and FPI

As shown in figure 5(a), the fitting relationship between penetration and FPI is established by the tunneling data recorded on site.

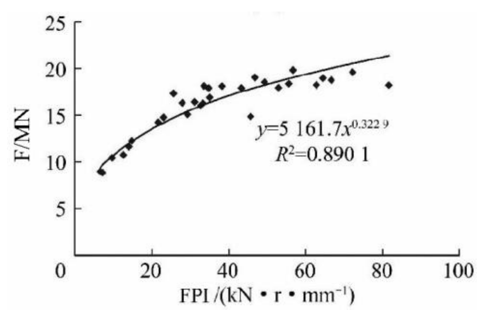
$$P = 0.001\,8FPI^2 - 0.281\,8FPI + 14.724 \ (R^2 = 0.951\,1) \tag{8}$$

Where P is the penetration. The regression coefficient (R^2) for this equation is 0.9511. It can be seen that there is a high correlation between P and FPI. Filed penetration index (FPI) can well represent the difficulty of TBM tunneling, namely boreability.

In this way, given the engineering surrounding rock conditions, the value of the FPI and P can be calculated according to formulas (7) and (8) respectively. And then the P multiplied by the cutterhead rotational speed to get the TBM advance speed, thereby to get the TBM tunneling performance under different rock mass conditions.



(a)



(b)

Figure 5. Correlation of Penetration, thrust and FPI.

5.4. Fitting Relationship between Thrust and FPI

According to the actual TBM driving data, the fitting relationship between the cutterhead thrust and FPI is established as Eq. (9) and figure 5(b).

$$F = 5\ 161.7FPI^{0.322\ 9} \quad (R^2 = 0.890\ 1) \tag{9}$$

Where F is cutterhead thrust.

In this way, based on the FPI, the TBM thrust required in different surrounding rock can be estimated by the Eq. (9), which can not only be used as a reference for the operation value of TBM thrust, but also can judge whether the TBM designed thrust is sufficient.

6. Rock Classification Based on FPI for TBM Tunnels

If the surrounding rock is extremely hard, complete, and abrasive, it is no need to support but difficult to penetration. And if the surrounding rock is weak and broken, it is easy to penetration but the support is too large or even make TBM trapped. Therefore, the TBM penetration, support and construction risk should be considered in the project planning and construction period analysis. From the rock mass boreability and TBM adaptability, the surrounding rock classification is carried out based on TBM construction characteristics.

According to different FPI corresponding to different tunneling performance, rock mass and support measures in the actual projects, the giant porphyry granite in this project is divided into three classes and summarized in table 4.

Table 4. Rock classification based on FPI for TBM tunnels.

Class	FPI	Thrust (MN)	Penetration (mm/r)	Geological conditions and support measures	Comment
I	$30 < FPI \leqslant 50$	16~18	5.5~8.5	Suitable rock hardness, developed joints and good stability. No need for support.	Excellent for TBM tunneling
II	$10 < FPI \leqslant 30$	13~16	8.5~12	Low rock hardness, less joints and minor instabilities. Local support.	Suitable for TBM tunneling
	$50 < FPI \leqslant 60$	18~19	4.5~5.5	The rock is relatively hard with less joints and minor instabilities. Local support.	
III	$FPI \leqslant 10$	<13	>12	Broken rock mass and instabilities. Need for strong support.	Extremely difficult for TBM tunneling
	$FPI > 60$	>19	<4.5	The rock is extremely hard and the joints are poorly developed.	

7. Discussion

(1) Regarding the influence of geological factors on rock mass boreability and tunneling performance, the key factors, tiny factors and collinear factors should be distinguished. Considering that TBM technology and design parameters make TBM tunneling parameters adjustable in a wider range, the influence of minor geological factors and collinear factors should be filtered out based on actual tunneling data. The proposed TBM tunneling performance prediction model may be more simple, practical and accurate.

(2) This study is based on the TBM field data of giant porphyritic granite. The data, relationships and research methods obtained have reference value for the evaluation of boreability, the prediction of tunneling performance, the design of TBM main parameters, as well as the prediction of construction period and cost of a TBM project. Next, based on more engineering cases with different lithology and surrounding rock conditions, it is expected to obtain a more complete, practical and accurate evaluation system for rock mass boreability and TBM tunneling performance.

(3) The surrounding rock conditions of the engineering in this paper are generally good. Although the advance rate and penetration change with surrounding rock over a wide range, the construction risk is no higher. Considering the serious adverse geological conditions of other projects, such as the rock large deformation, loose aquifer and extremely strong rock burst, the surrounding rock should be worse than the "third class" in this paper, which will bring serious challenges and major risks for TBM construction, so the above "third class" of surrounding rock can be further refined.

8. Conclusion

(1) The filed penetration index (FPI) is given as an index to measure the ease and speed of TBM construction. The correlation analysis shows that the main factors are uniaxial compressive strength (UCS) and rock mass integrity coefficient (Kv), and other factors can be ignored. Furthermore, a multiple regression equation of FPI and key geological factors (UCS and Kv) was established as $FPI = \exp(0.01UCS + 1.091K_v + 1.653)$.

(2) The fitting equation between penetration (P) and filed penetration index (FPI) of TBM is put forward as $P = 0.001\,8FPI^2 - 0.281\,8FPI + 14.724$, and the fitting relation between cutterhead thrust (F) and FPI is proposed as $F = 5\,161.7FPI^{0.322\,9}$. In this way, given the uniaxial compressive strength (UCS) and rock mass integrity coefficient (Kv), the penetration, advance speed and required thrust can be predicted for a TBM tunnel project.

(3) The rock classification based on FPI for TBM tunnels is proposed. This method takes into account the characteristics of TBM construction and the surrounding rock is finally classified from the boreability of rock mass and the adaptability of TBM, which can meet the requirements of TBM tunneling.

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