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Modeling and Prediction for the thrust on EPB TBMs under different geological conditions by considering mechanical decoupling

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EPB TBMs (Earth pressure balance Tunneling Boring Machines) are extensively used in tunneling constructions because of its high efficiency and low disturbance on structures above ground. It is critically significant to predict the thrust acting on TBMs under different geological conditions for both the design of power system and the control of tunneling process. The interaction between the cutterhead and the ground is the core of excavation, through which geological conditions determine the thrust re-quirement combined with operating status and structural characteristics. This paper conducted a mechanical decoupling analysis to obtain a basic expression of the cutterhead-ground interactive stress. Then more engineering factors (such as cutterhead topological structure, underground overburden, thrusts on other parts, etc.) were further considered to establish a predicting model for the total thrust acting on a machine during tunneling. Combined with three subway projects under different geological conditions in China, the model was verified and used to analyze how geological, operating and structural parameters influence the acting thrust.

EPB TBMs, thrust prediction, different geological conditions, mechanical decoupling

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1 Introduction

Due to the impetus of city development, significant attention has been paid to tunneling constructions for a better use of urban underground space [1]. EPB TBMs are a kind of typical equipment for underground construction with high efficiency and low disturbance on structures above ground. The tunneling of an EPB TBM is a complex process depending on geological conditions (soil/rock mass properties), operating status (the rate of penetration, the cutterhead rotating speed, etc.) and machine's structure (cutterhead topology structure, size, etc.). The thrust acting on the machine is one of kernel control parameters during tunneling. Predicting the thrust under different geological conditions is of great importance for directing a better control and improving the performance of EPB TBMs. Particularly it is essential to not only estimate the thrust value, but also know what factors and how they affect the thrust. Moreover, the results are helpful in the design of the machine's power system.

Currently in the circle of engineering, the thrust is esti-

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mated mainly based on an empirical formula proposed by Krause, through collecting and analyzing data sets obtained from projects using more than 400 shield machines (see Figure 1) [2]. Due to its concision and wide range of applications, the empirical formula provides fundamental reference for thrust prediction for years. However, it is obviously not accurate enough within a large estimated range. Especially, there is little knowledge about how to select empirical coefficient under different geological conditions. The uncertainty of empirical coefficient selection may lead to a too big safety margin in design or faults in control (see Table 1 [3]). Furthermore, the influence of main factors on the thrust is not given in the empirical formula.

Research has been done to reveal the influence of factors related to thrust prediction. Early statistical work conducted by Szechy recommended 600 kN/m^2 as the empirical thrust value per unit area on tunneling interface [4]. Since then a number of experimental investigations have been performed by researchers in laboratory. Gertsch et al. [5] presented a linear relationship between the penetration and the normal force by full-scale laboratory disc cutting tests. TBM penetration test under different *in situ* stress conditions also showed that the thrust increased approximately linearly with the penetration [6]. Cho et al. [7] studied forces acting on cutters with different spaces by linear-cutting-machine testing. Jakobsen et al. [8] developed a Soft Ground Abrasion Tester for evaluating how soil conditions affect the thrust. Due to high cost and extreme complexity of the related experiments, numerical simulations become popular and important for modeling tunneling process. Su et al. [9] introduced a finite element analysis of a TBM's cutterhead excavating process and calculated forces using either panel-type cutterhead or spoke-type cutterhead. 3D numerical simulation models were proposed to calculate the thrust of TBM tunneling in soft ground by Kasper and Meschke [10] and in squeezing grounds by Hasanpour et al. [11]. The dynamic characteristics of cutterhead were analyzed by Sun et al. [12] and by Huo et al. [13]. Besides, some statistical methods were developed and applied to engineering data analysis of TBMs. In particular, Torabi et al. [14] presented a model of artificial neural network from engineering data to study the influence of geotechnical parameters on TBM performance. Mahdevari et al. [15] discussed the relationship between penetration rates and TBM forces using support vector regression. The statistical relationships between TBM diameter and installed thrust capacity were studied based on a database including 262 TBMs' design parameters by Ates et al. [16]. Copur et al. investigated the stochastic characteristics of EPB TBM excavation by implementing a stochastic model into a deterministic model [17]. Zhang et al. [18,19] proposed an inverse method on *in-situ* data for predicting the performance of an EPB TBM and its thrust.

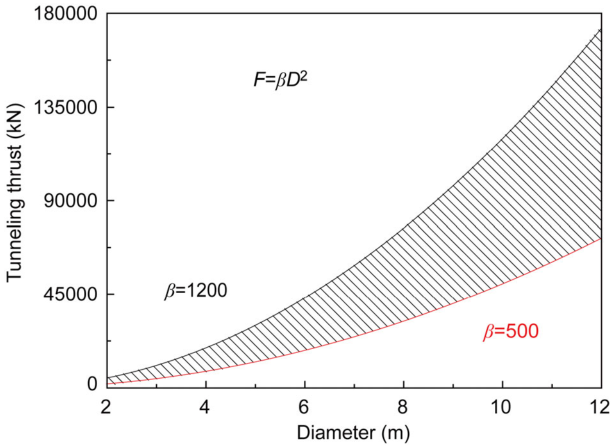


Figure 1 Krause empirical formula.

Table 1 Values of empirical coefficient β in some projects [3]

Projects	Geological conditions	Diameter (m)	Thrust (kN)	β
Guangzhou No.3 Subway Kecun-Datang in China	Pelitic siltstone	6.25	33526	858
Beijing No. 5 Subway Test Section in China	Silty clay/ Sand pebble	6.19	27783	725
Nanjing No.1 Subway Xuanwu Gate-Xu Fu Lane in China	Silty clay	6.40	31670	773
Beijing Liangshui River Sewage Tunnel in China	Sand pebble	3.64	12000	906
Shanghai Huangpu Tourist Tunnel in China	Muddy clay	7.65	52000	889

Although the research by lab experiments, numerical simulations and engineering data analysis mentioned above has shown some useful results of the relationship among different parameters, it is still important in terms of design and control on development of analytical models to describe this relationship scientifically and then predict the thrust under different situations. To this end, Festa et al. [20] analyzed forces acting on TBMs and separate them into active ones (controllable ones due to ground-machine interaction) and passive ones. Sugimoto and Sramoon [21] assumed a uniform stress distribution and computed force acting on the cutterhead by dividing interactive face into a finite number of small elements. Wang and Shangguan et al. [22,23] predicted the cutterhead thrust based on the amendment for the earth pressure at the excavating face. Besides, Wang et al. [24] and Rostami [25] conducted analytical mechanical investigations to estimate cutting forces acting on a disc cutter.

In the analytical studies reviewed above, methods used to estimate acting thrust were focusing on the equivalent earth pressure or uniform stress integration, which regarded the cutterhead and the ground as two separate parts without considerations of their coupling interaction. As a result, existing models are unable to reflect the comprehensive influence of geological conditions, machine's operating status and structural characteristics which determined the thrust simultaneously during tunneling. In practice, a TBM works as a coupled mechanical system in which the machine and the surrounding ground have significant interactions [26,27]. Therefore, a reasonable decoupling analysis of the interactions is required to predict thrusts more accurately under different geological and operating conditions.

In this paper, mechanical analysis for an EPB TBM under working condition was conducted to analyze sources of the thrust. Then we focused on the coupling interaction between the cutterhead and the surrounding ground which was the core for predicting. It was decoupled through solving equilibrium differential equations of the ground under boundary conditions which were determined by interactive characteristics of the coupling interface. With further considering of several engineer factors, a theoretical model was then established for predicting the acting thrust. In addition, three subway projects under different geological conditions in China were considered to verify the model and discuss the influence of geological, operating and structural parameters on the thrust.

2 Mechanical analysis for the thrust acting on EPB TBMs

During tunneling, thrust and torque are simultaneously acting on an EPB TBM. The thrust is the drive force to make the machine advance. The torque is used to keep the cutterhead rotating. This paper focuses on the thrust. Figure 2 shows the mechanical diagram in advance direction of an EPB TBM working underground. According to equilibrium, the total thrust F acting on the machine equals to the sum of resistance forces in advance direction. The equilibrium equation in advance direction is

$$F{=}F_1+F_2+F_3, \tag{1}$$

where F_1 is the resistance force acting on the cutterhead; F_2 is the frictional force between the shield skin plate and the ground; F_3 is the tractive force of the back-up system. Besides, there are still some other resistance forces, such as the frictional force between the lining and the tail of shield, the turning resistance force, etc. Compared with those three main parts, they are a small proportion only (less than 5% of the total thrust) [28] and we ignore it during analysis.

The resistance force acting on the cutterhead is the most complex one which is determined by the coupling interaction between the cutterhead and the ground on excavating interface. It gives a real-time response to the variation of geological condition and the adjustment of machine's operating status. This force is hard to be predicted because of its fluctuant characteristics, while the other ones are relatively stable during excavating although they account for a substantial percentage of the total.

The frictional force F_2 between the shield skin plate and the ground can be calculated by [19]

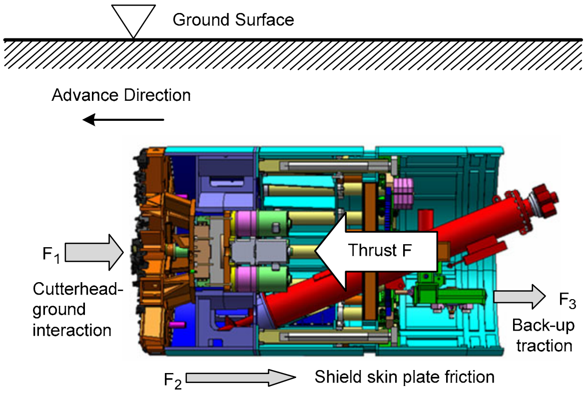


Figure 2 (Color online) Mechanical diagram in advance direction.

$$F_2=f_1\cdot\left(\pi D\cdot L\cdot P_m+W\right), \tag{2}$$

where f_1 is the frictional coefficient between the shield skin plate and the ground; D (m) is the diameter of the shield; L (m) is the length of the shield skin plate; P_m (kPa) is the average earth pressure acting on the shield skin plate; W (kN) is the weight of the main part of the machine.

The tractive force of the back-up system F_3 can be expressed as

$$F_3=f_2\cdot W_b, \tag{3}$$

where f_2 is the frictional coefficient between the back-up system and the track; W_b is the weight of the back-up system.

The force acting on the cutterhead, determined by the cutterhead-ground interaction and simultaneously influenced by geological condition, operating status and machine's structure, will be intensively studied in section 3.

3 Modeling of the cutterhead-ground interaction by considering mechanical decoupling

From the mechanical point of view, the excavating process is essentially coupling interactions between the cutterhead and the ground, which are affected by geological condition, operating status, and machine's structure. These interactions include the squeezing in advance direction which is related to the thrust, and the friction and cutting in rotating direction which are related to the torque. In this paper we focus on the cutterhead-ground squeezing force for predicting the thrust. The decoupling analysis through mechanical method is the key point of this work.

The interactive system consisting of the cutterhead and the ground is decoupled here based on contact mechanics. An approximate cutterhead-ground squeezing model for mechanical analysis is established as shown in Figure 3. The cutterhead-ground interaction is the internal force of the system, which needs to be exposed to a pair of acting and

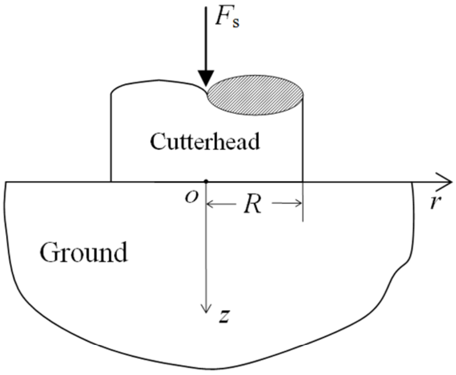


Figure 3 Mechanical model of cutterhead-ground squeezing.

reacting forces through separating the cutterhead and the ground. We regard the cutterhead as a rigid body during analysis since its stiffness is much higher than the stiffness of the ground. A decoupling description of the model in Figure 3 will be obtained through solving equilibrium differential equations of the ground under boundary conditions determined by interactive characteristics of the coupling interface.

Equilibrium differential equations for the ground squeezed by the cutterhead are established as control equations of the model. Those equations are expressed by axisymmetric displacements $\{u_r, u_z\}$ of the ground in the cylindrical coordinates $\{r, \theta, z\}$ as follows:

$$\begin{aligned}&\frac{1}{1-2\mu}\frac{\partial}{\partial r}\left(\frac{\partial u_r}{\partial r}+\frac{u_r}{r}+\frac{\partial u_z}{\partial z}\right)+\nabla^2 u_r-\frac{u_r}{r^2}=0,\\&\frac{1}{1-2\mu}\frac{\partial}{\partial z}\left(\frac{\partial u_r}{\partial r}+\frac{u_r}{r}+\frac{\partial u_z}{\partial z}\right)+\nabla^2 u_z=0,\end{aligned} \tag{4}$$

where μ is Poisson's ratio of the ground.

The boundary conditions determined by interactive characteristics on the interface z=0 are

$$\begin{aligned}&u_z(r,0)=\delta, \quad (0\le r\le R),\\&\sigma_z(r,0)=0, \quad (r>R),\end{aligned} \tag{5}$$

where δ (mm/rev) is the penetrating depth per revolution of the cutterhead which includes both the influence of the rate of penetration and the cutterhead rotating speed, R (m) is the cutterhead radius.

Appling Hankel transform to the differential equations (eq. (4)) under the boundary conditions (eq. (5)) [29], normal squeezing stress acting on interactive face z=0 of the model in Figure 3 can be obtained as follows:

$$\sigma_z(r,0)=\frac{E}{(1-\mu^2)\pi\sqrt{R^2-r^2}}\delta, \tag{6}$$

where E (kPa) is Young's modulus of the ground.

Eq. (6) gives a basic stress expression caused by the cutterhead-ground squeezing. On this basis, further consideration of the influence of some engineering factors, mainly the topological structure of cutterhead and the overburden due to underground, should be carried out for calculating the thrust acting on the cutterhead.

Figure 4 shows the general topological structure of the cutterhead, including the closed area (panel and cutters) and the open area (connecting to the chamber). The squeezing force acts on the closed area, while the pressure inside the chamber is directly transferred to the ground through the open area to maintain the stability of excavating interface. Thus the cutterhead-ground interactive force F_s can be calculated by integrating the squeezing stress along the closed area and the chamber pressure along the open area, respectively:

$$\begin{aligned}F_s=&\int_0^R\int_0^{2\pi}(1-\eta)\cdot\frac{E}{(1-\mu^2)\pi\sqrt{R^2-r^2}}\delta\cdot r\mathrm{d}\theta\mathrm{d}r\\&+\int_0^R\int_0^{2\pi}\eta\cdot p_m\cdot r\mathrm{d}\theta\mathrm{d}r,\end{aligned} \tag{7}$$

$$F_s=\frac{2E(1-\eta)}{1-\mu^2}\delta R+\pi R^2\eta p_m, \tag{8}$$

where η is the opening ratio of the cutterhead.

Besides, earth pressure at rest is also acting on the closed area of the cutterhead, which is caused by the overburden. We consider it independent of excavating process and proportional to the overburden depth. It can be computed through integrating the earth pressure of one point underground in soil mechanics theory along the acting area.

$$F_e=\int_0^R\int_0^{2\pi}(1-\eta)\cdot K_0\gamma(H-r\sin\theta)\cdot r\mathrm{d}\theta\mathrm{d}r, \tag{9}$$

$$F_e=\pi R^2(1-\eta)K_0\gamma H, \tag{10}$$

where K_0 is the earth pressure coefficient at rest; γ(kN/m^3) is the bulk density of the ground; H (m) is the depth of ma-

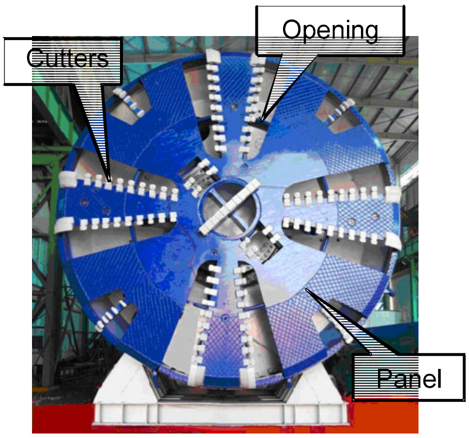


Figure 4 (Color online) Topological structure of the cutterhead.

chine's central axis.

Then the thrust acting on the cutterhead can be approximately calculated by

$$F_1=\frac{2E\left(1-\eta\right)}{1-\mu^2}\delta R+\pi R^2\eta p_m+\pi R^2\left(1-\eta\right)K_0\gamma H. \quad (11)$$

Eq. (11) indicates that the thrust acting on the cutterhead F_1 is affected by geological parameters E, μ, K_0, γ, H, operating parameters δ, p_m and structure parameters R, η. To analyze effects of these factors on the thrust, curves of the cutterhead thrust with respect to the penetrating depth under three kinds of typical geological conditions are presented in Figure 5. The cutterhead thrust increases linearly with the penetrating depth per revolution. Moreover, different geological conditions result in different curve slopes. In other words, geological conditions affect not only the value of thrust, but also the changing rate of the thrust increasing with the penetrating depth.

4 Case study for the thrust model

To sum up, the thrust acting on an EPB TBM during service can be approximately predicted by the model:

$$\begin{aligned}F=&\frac{2E\left(1-\eta\right)}{1-\mu^2}\delta R+\pi R^2\eta p_m+\pi R^2\left(1-\eta\right)K_0\gamma H\\&+f_1\cdot\left(\pi D\cdot L\cdot P_m+W\right)+f_2\cdot W_b.\end{aligned} \quad (12)$$

Further discussion on the application of the model is conducted by considering several projects under different geological conditions. They are sections from No. 9 subway of Tianjin in China, No. 9 subway of Beijing in China and No. 2 subway of Shenzhen in China. The validity and effectiveness of the model are discussed by comparing the thrust predicted by the proposed model, the *in-situ* recorded value during construction and the empirical range given by Krause formula.

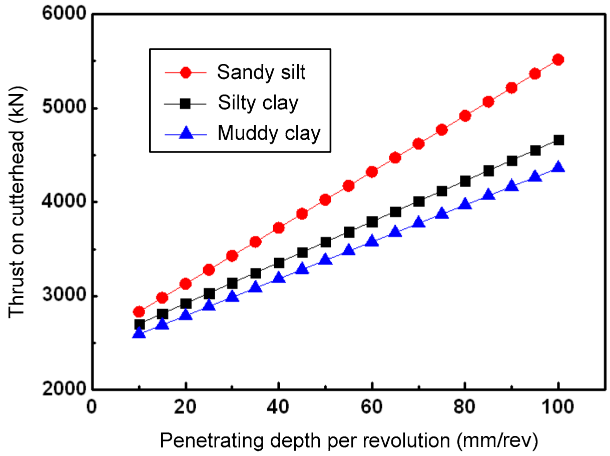
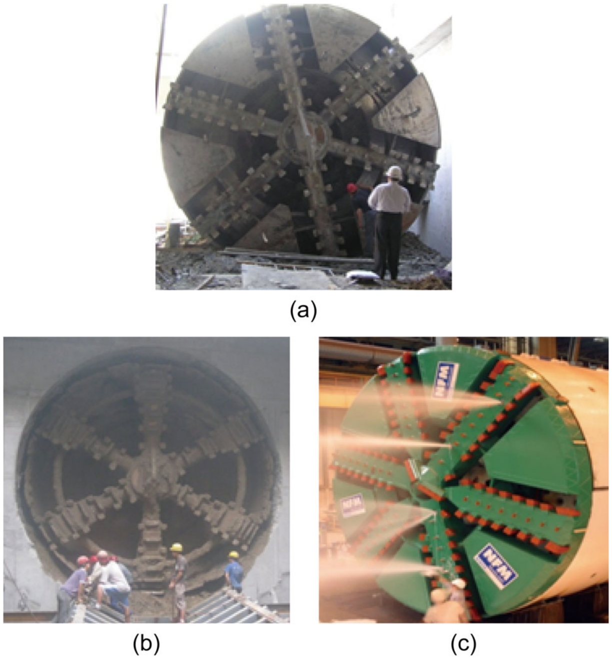


Figure 5 (Color online) Variations of the cutterhead thrust with the penetrating depth under different geological conditions.

The discussed section from Tianjin No. 9 subway project was constructed under geological condition of soil, which mainly consists of silty clay, silt, silty sand and muddy clay with an overburden of 10 to 15 meters. An EPB TBM, manufactured by Komatsu Company in Japan with a diameter of 6.34 m and an opening ratio of 44% panel type cutterhead (see Figure 6(a)), was used. The section from Beijing No. 9 subway project was mainly constructed under geological condition of sand pebble, with an overburden of 8 to 11 meters. An EPB TBM, manufactured by JTSC Company in Japan with a diameter of 6.14 m and an opening ratio of 70% spoke type cutterhead (see Figure 6(b)), was used. The section from Shenzhen No. 2 subway project was constructed under a combined geological condition of soil and soft rock, with an overburden of 9 to 12 meters. An EPB TBM, manufactured by NFM Company in France with a diameter of 6.28 m and an opening ratio of 28% panel type cutterhead (see Figure 6(c)), was used.

During tunneling process, operating parameters were recorded by sensors installed on the machine (see Table 2). Geological parameters involved in the analysis are referred from geological survey reports. Some main geological parameters are shown in Table 3. The structural parameters are referred in the machine's drawings. All of these provide the data basis for the analysis of this paper. By substituting these parameters into the proposed model (eq. (12)), thrusts in these three projects can be obtained.

Figure 7 shows the comparison among predicted values by proposed model, *in-situ* recorded ones during construction and empirical ranges by Krause formula. Compared


(a)

(b) (c)

Figure 6 (Color online) Cutterheads used in three projects: (a) Tianjin No.9 subway project; (b) Beijing No.9 subway project; (c) Shenzhen No.2 subway project.

Table 2 Main operating parameters in the three projects

Projects	Rate of penetration (mm/min)	Cutterhead rotation speed (rev/min)	Penetrating depth per revolution (mm/rev)	Chamber pressure (kPa)
Tianjin No. 9 subway project	17–55	0.4–1.1	19–56	160–325
Beijing No. 9 subway project	12–82	0.8–1.0	14–92	40–130
Shenzhen No. 2 subway project	12–60	1.0–1.4	11–54	113–220

Table 3 Main geological parameters in the three projects

Geology	Young's modulus (kPa)	Poisson ratio	Earth pressure coefficient	Bulk density (kN/m^3)
Silt in Tianjin	7.6	0.29	0.40	21.1
Silty Sand in Tianjin	8.9	0.23	0.30	24.7
Muddy Clay in Tianjin	4.4	0.44	0.80	18.7
Silty Clay in Tianjin	5.6	0.29	0.40	20.4
Sand Pebble in Beijing	33	0.20	0.25	21.1
Moldable Silty Clay in Shenzhen	5.6	0.30	0.45	19.6
Moldable Gravelly Sand in Shenzhen	18	0.29	0.43	17.2
Hard Plastic Gravelly Sand in Shenzhen	20	0.30	0.43	17.8
Completely Weathered Granite in Shenzhen	80	0.26	0.39	18.8
Strongly Weathered Granite in Shenzhen	100	0.25	0.43	19.4

with empirical ranges, recorded values of the thrust are just around or even much smaller than the lower bounds in these projects. Considering safety coefficients, the ranges given by Krause empirical formula are still too broad and conservative. It needs more additional information for a better design and control of EPB TBMs. As the proposed model considers the comprehensive influence of geological condition, operating statue and structure characteristics of the machine, predicted thrusts are basically consistent with recorded values in all these projects under different geological conditions.

Through the results of those three cases, it is shown that the predicted thrust given by the model reflects the influence of three main kinds of engineering factors. Geological parameters are crucial for the acting thrust. Generally, the thrust increases significantly under a high modulus ground. Operating parameters (eg. penetrating depth per revolution) affect the thrust combined with geological condition, which causes the fluctuation of the acting thrust. Structural parameters will not change during the tunneling process, but they determine the basic level of the thrust.

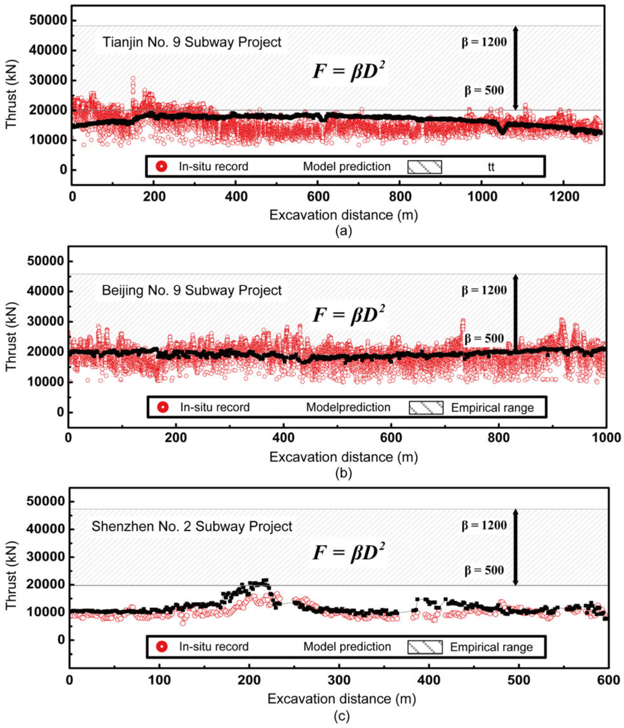


Figure 7 (Color online) Comparison among model predicted thrust, *in-situ* recorded thrust and empirical thrust range in the three projects: (a) Tianjin No. 9 subway project; (b) Beijing No. 9 subway project; (c) Shenzhen No. 2 subway project.

In addition, proportions of the thrust acting on each main part in these projects are calculated from the proposed model, shown in Figure 8. Bar graphs in colors show average proportions during the whole tunneling process combined with black lines giving variation ranges of proportion in each project. In Tianjin No.9 subway project constructed in soft soil, the thrust acting on the shield skin plate occupies a major part of 58.16% of the total thrust, while the proportion of the cutterhead thrust is only 38.15%. By contrast, the cutterhead thrust in Shenzhen No.2 subway project is a large part of 76.20% of the total to accomplish the excavation in ground including soft rock. Besides, soil-rock mixed geology causes fluctuations in proportions during tunneling. Except geological condition, other factors such as structural characteristics are also influence the acting thrust. Although the condition of sand pebble in Beijing No.9 subway project is supposed to require a higher level of cutterhead thrust than the one with soil, using a spoke type cutterhead with a large open ratio (70%) in that project results in a smaller proportion 28.68% of cutterhead thrust. The cutterhead used in Tianjin No.9 project has an opening ratio of 44%, which results in a larger friction between cutterhead's panel and ground. In all three projects, thrusts on the back-up system are less than 5% of the total. As shown, proportions of the thrust acting on each main part are determined by geological condition, operating status and structural characteristics of the machine together.

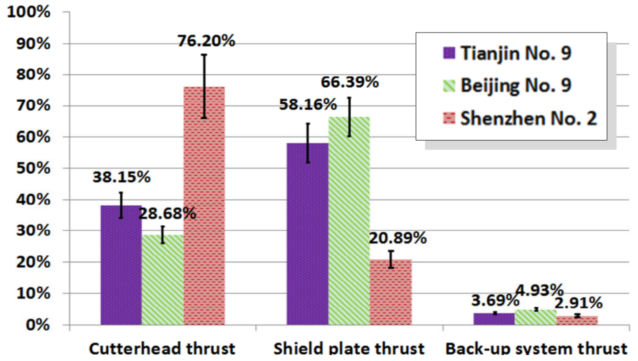


Figure 8 (Color online) Proportions of the thrust acting on each main part.

5 Conclusions

Analytical methods in mechanics were used to solve the coupling interactive problem between EPB TBMs and the surrounding ground in the paper. A decoupling description of the cutterhead-ground interaction was obtained through solving equilibrium differential equations of the ground under coupling interactive boundary conditions. With further consideration of several engineering factors, a thrust-predicting model considering the influence of geological condition, operating status and structural characteristics was established and then discussed through three projects under different geological conditions.

The thrust is highly dependent on geological conditions. Besides, operating parameters affect the thrust combined with geological condition, which causes the fluctuation of the thrust. Although structural parameters will not change during the tunneling process, they determine the basic level of the thrust. These factors also result in different proportions of thrust components acting on each part of the machine. The work can be taken as a reference for both the design of power system and the adjustment of parameter during tunneling by EPB TBMs.

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