Mechanical Analysis and Prediction for the Total Thrust on TBMs

Siyang Zhou[1], Yilan Kang[1], Cuixia Su[2], and Qian Zhang[1(✉)]

[1] Tianjin Key Laboratory of Modern Engineering Mechanics, Tianjin, China
zhangqian@tju.edu.cn
[2] China Railway Construction Heavy Industry Group Limited, Changsha, China

Abstract. This paper proposed a new model to predict the total thrust acting on Tunnel Boring Machines (TBMs) based on mechanical analysis. Key parameters involved in the prediction are mainly rock property, operating status and structural feature. Several force components which the total thrust consists of were analyzed. Considering failure criterion, mechanical analysis of the interaction between the rock and the cutterhead was carried out. Furthermore, the comparison was performed between the predicted value and the in-situ measured data of the thrust in a TBM engineering project. The results show that this approximate predictive model is able to reflect the global trend of the acting thrust due to considering geological, operating and structural feature.

Keywords: TBM · Total thrust · Predictive model · Mechanical analysis

1 Introduction

Tunnel boring machines are a kind of hard rock excavating equipment. It takes advantages of high penetration rate and small disturbance on the surrounding environment, thus has been widely used in underground constructions. Due to its complex structure, heavy power, and particularly under complicated geological conditions, there are high requirements on TBMs' parameters control during design and operating process. The total thrust acting on TBMs that reflects the interaction between the machine and the rock is one of the essential parameters. Predictions of the total thrust for TBMs are indispensible for optimizing the design and control during construction.

Recently, there is some relevant research on loads in TBM tunneling progress. In regard to theoretical approaches, Colorado School of Mines (CSM) prediction model developed an estimation of forces based on a uniform distribution of contact pressure between a cutter and the rock[1]; Roxborough et al.[2] analyzed cutting forces of a wedge-shaped cutter by taking into account the contact area and the compressive strength of rock. By using the stress distribution in the Hertz's elastic contact, Sun et al. [3]provided a predictive model on cutting forces, power and energy consumption were also discussed on the basis of cutter load analysis. Wu et al.[4] applied the theory of dimension to calculate normal forces of cutter, and he used the

H. Liu et al. (Eds.): ICIRA 2015, Part III, LNAI 9246, pp. 436–444, 2015.
DOI: 10.1007/978-3-319-22873-0_39

laboratory cutting tests and engineering data to obtain empirical equation.Considering the geometric feature of the contact area between cutters and the rock, Wijk [5]developed predictive formulas to estimate the thrust and torque on a wedge-shaped cutter. Based on mechanical analysis of the disc cutters, prediction of disc cutter wear and specific energy(SE) was investigated by Wang et al.[6].

In respect of experimental work and numerical simulation, Snowdon et al.[7] used laboratory experiments to analyze tool cutters forces and specific energy under four kinds of rock at various spacing and penetration. Rostami et al.[1] studied the form of contact pressure distribution, a regression analysis between measured cutting forces and cutting parameters was utilized to develop an estimate of the pressure. Gong et al.[8] discussed the influence of frictional force by field test and friction experiment, and a rock mass boreability analysis was given. Ma et al.[9] carried out a numerical study on the effect of confining stress on rock fragmentation. To provide a better estimate of the influence on total thrust force, Su et al.[10] analyzed several parameters such as the cutterhead opening ratio and the chamber pressure.

As for engineering data analysis, Yagiz et al.[11]. suggested improvements should be made to conventional CSM model where they conducted investigations on the effect of rock mass fracture and brittleness. Zhang et al.[12]proposed a method for inverse analysis and modeling based on mass on-site measured data, in which dimensional analysis and data mining techniques were combined. In addition, an identification and optimization method for the energy consumption of a shield tunnel machine was presented[13]. In the light of cutter force analysis, a multi-objective genetic algorithm (MOGA) was applied to improve the quality of the disc cutters' plane layout by Huo et al.[14] Zhao et al.[15] studied various geological parameters' effects on rock fragmentation, they concluded that UCS is the most crucial factor, and a statistical prediction model is set up by performing a nonlinear regression analysis. Hassanpour et al.[16] made use of the available data and found strong relationships between geological parameters and field penetration index (FPI). Based on statistical approaches, Torabi et al.[17] ranked the effectiveness of four selected geological parameters on penetration rate in a descending order as follows: UCS, friction angle, Poisson's ratio, and cohesion.

In conclusion, research based on rock experiment, numerical simulation and data analysis did provided valuable results of the relationship between thrust force requirements and various parameters. Moreover, theoretical analysis is essential to study the intrinsic relationship between various crucial factors. However, the majority of related works with regard to TBM load are focused on the cutter force, global mechanical analysis of equipment during excavation is currently lacking, which can give a fully understand of thrust force requirement for TBM with different geological and operational conditions.

This paper carried out a global mechanical analysis of TBMs during excavation. Several force components of the total thrust were analyzed. Considering specific failure criterion, mechanical analysis of the interaction between the rock and the cutterhead was carried out. A model was established to predict the total thrust acting on TBMs with different geological and operational conditions. The comparison was performed between the predicted value and the in-situ measured data of the thrust in a TBM engineering project.

2 Mechanical Analysis and Modeling of the Total Thrust on TBMs

This paper studied the total thrust of the whole equipment, and mechanical analysis along advancing direction (Fig.1) was discussed. According to the mechanical equilibrium along advancing direction during excavation, the total thrust is supposed to equal to the sum of resistance forces. These resistance forces mainly include: the force acting on cutterhead by the rock F_r (kN), friction force of shield F_f (kN), friction force of subsequent equipments F_b (kN).Therefore, the total thrust F (kN) on a TBM can be expressed as:

$$F = F_r + F_f + F_b \tag{1}$$

When advancing, the cutterhead is in contact with the tunneling interface. Resistance forces are determined by the interaction between cutters and the rock. At present, constant cross section (CCS) cutters are commonly adopted, so the paper mainly discussed CCS cutters. From the perspective of mechanics, the excavating progress of TBM is essentially a continuous interaction between tunneling interface of rock and cutters, which is under the confining pressure of surrounding rock. The primary resistance force is the force acting on the cutterhead by the rock. Results of full-scale laboratory cutting tests indicated that a uniform pressure distribution along the cutter penetration edge can be used in most cases for CCS cutters[1]. Taking a random infinitesimal body of rock in contact with the arc surface of cutter to analyze the stress state (Fig.2), the infinitesimal body is under the confining pressure and cutters' pressure simultaneously.

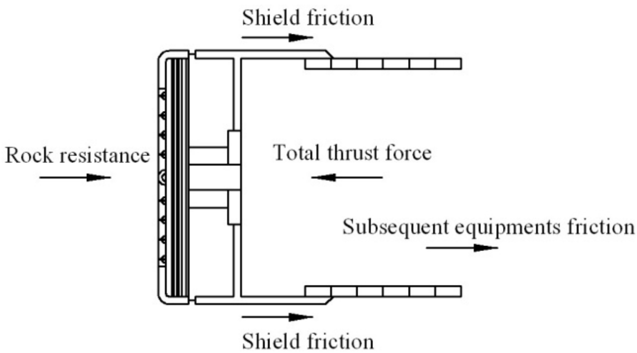

Fig. 1. Forces at TBM along advancing direction.

If the disc is free rolling and neglecting friction[2], the disc cutter is only under the load of radial pressure σ_1 (pointing towards the center) from the rock(ignoring the shearing stress). Based on shearing stress theorem, the side face of the infinitesimal body is under confining pressure σ_3 perpendicular to side face.

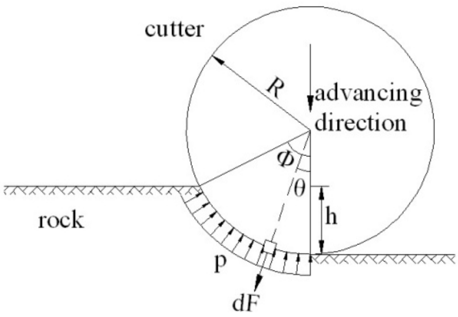

Fig. 2. Mechanical analysis of a cutter.

In the process of excavation, rock is broken by the crushing of cutter. Shear failure occurs under compression status[18]. On the basis of Mohr-Coulomb criteria, the limiting shearing stress of infinitesimal body depends on the friction angle and cohesion of rock[19].

$$\tau = c + \sigma \tan \varphi \tag{2}$$

Where τ (MPa) is shearing stress on failure surface; c (MPa) is rock cohesion; σ (MPa) is normal stress on failure surface; φ (rad) is rock friction angle.

According to the Mohr's stress circle , the limiting radial pressure can be obtained:

$$\sigma_1 = \frac{1+\sin\varphi}{1-\sin\varphi}\sigma_3 + \sigma_c \tag{3}$$

Where σ_c is the uniaxial compressive strength, namely the limiting stress without confining pressure[20,21].

Because of the pressure distribution along the cutter penetration edge is nearly uniform, normal forces F_n can be estimated by:

$$F_n = \int_0^{\phi} TR\sigma_1 d\theta \cos\theta \tag{4}$$

Where F_n is normal forces; T (mm) is cutter tip thickness; R (mm) is cutter radius; θ (rad) is the radian between radical pressure and advancing direction; ϕ (rad) is the radian of arc surface, which can be obtained by geometrical relationship: ϕ=arccos$(\frac{R-h}{R})$, h is the penetration.

Putting (3) in (4) and making integral calculation, thus the normal force is obtained:

$$F_n = TR(\frac{1+\sin\varphi}{1-\sin\varphi}\sigma_3 + \sigma_c)\sin\phi \tag{5}$$

As it is known to all, TBM cutterhead is usually equipped with dozens of cutters. Despite there has certain discrepancy among cutters in different places, it is appropriate to assume that they are the same from a statistical perspective when analyzing global mechanical issue. Therefore, the total cutting force of cutterhead can be nearly expressed as:

$$F_r = \sum_{i=1}^{N} F_i \approx NF_n \tag{6}$$

Where F_r (kN) is the force acted on cutterhead by the rock; F_i (kN)is the normal force of single cutter

In order to reduce the vibration and to prevent jamming accidents, TBM should adjust shield position to make the shield contact with the tunnel wall under smaller pressure[22]. As a consequence, there exist frictional forces between shield and rock, and it is determined by contact stress, friction coefficient and shield size:

$$F_f = \mu_1 \pi D l \frac{\Theta}{360^0} P \tag{7}$$

Where F_f is the friction force between shield and tunnel wall; μ_1 is the friction coefficient between shield and tunnel wall; D (m) is cutterhead diameter; $l(m)$ is the length of shied; $\Theta(^\circ)$ is the extent of contact area between shield and tunnel wall; P (MPa) is the contact pressure determined by contact conditions.

In order to reduce the vibration and to prevent jamming accidents, TBM should adjust shield position to make the shield contact with the tunnel wall under smaller pressure[23]. As a consequence, there exist frictional forces between shield and rock, and it is determined by contact stress, friction coefficient and shield size:.

$$F_d = \mu_2 mg \tag{8}$$

Where μ_2 is friction coefficient between subsequent equipments and track; m (t) is the weight of subsequent equipments; g (m/s^2) is the acceleration of gravity.

By Summing up force components mentioned above, an approximate predictive model of thrust force is established (equation(9)). Moreover, this proposed model involves the relationships between the thrust and the geological, operating, and structural parameters, and it is a reasonable prediction from the perspective of mechanical analysis.

$$F = F_r + F_f + F_b = NTR\left(\frac{1+\sin\varphi}{1-\sin\varphi}\sigma_3 + \sigma_c\right)\sin\phi + \mu_1 \pi D l \frac{\theta}{360^0} P + \mu_2 mg \tag{9}$$

3 Case Study

Data collected from one hard rock TBM tunnel (the Dahuofang Water Conveyance Tunnel) was utilized to verify the predictive capability of presented model. Influences of geological and operating parameters on the thrust were investigated. In this literature, a section of the tunnel being about 4.5 km long was excavated with open-type TBM.

Several main rock types have been identified in the study area as follows: tuffaceous siltstone, volcanic breccia, migmatite, etc, with uniaxial compressive strength ranges from 30~120MPa. Geological parameters for calculation were taken from the report of engineering geological exploration.

In this case study, cutterhead diameter is 8.03m, the length of the shield is 3m and the weight of subsequent equipments is 356t.The main structure parameters of cutter were demonstrated as follows: cutter radius is 241.5 mm; cutter tip thickness is 25mm; and there are 51 cutters on the cutterhead.

In addition, operating data derived from the control system of the machine were recorded in real-time: the rate of penetration ranges from 29~64mm/min, while the range for penetration is 4~13mm/rev.

The curves of predicted and measured thrust force were shown in Fig.3. As is illustrated in the graph, the red line stands for the actual measured data while the blue line represents the calculation result based on the predictive model. Besides, both of these two lines fluctuate between 5000kN to 20000kN.

The results revealed that the predicted one shows a good agreement with measured curve and fluctuates around it. For instance, when the advancing distance is between 700-1000m, the trend of the measured curve declines, and the predicted one also dropped. It could be concluded that the proposed model reflects the overall trend of thrust force, since it allows for the mechanical system consists of ground condition and equipment.

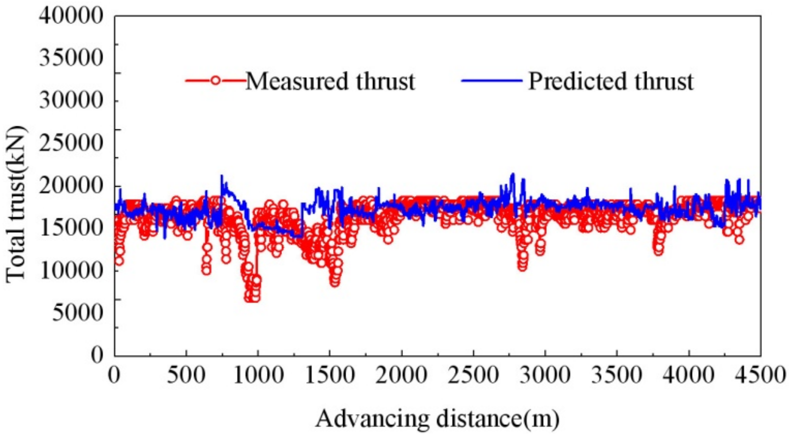

Fig. 3. Comparation between predicted thrust and measured thrust of Dahuofang project.

The second case study is about the measured data from Tunnel no.9 of Yintao Project, which is located in the Dingxi, Guansu Province. Different from the Dahuofang Water Conveyance Tunnel, this project was mainly accomplished by a double-shield TBM.

Complicated geological condition was encountered during excavation. The rock types not only include soft rock like argillaceous siltstone and conglomeratic sandstone, but also hard rock such as marble and granitic gneiss. Furthermore, the maximum uniaxial compressive strength is up to 95MPa while the minimum is only 2.5 MPa. Geological parameters for calculation were taken from the report of engineering geological exploration.

In this case study, cutterhead diameter is 5.75m, the length of the shield is 6m and the weight of subsequent equipments is 523t.The main structure parameters of cutter were demonstrated as follows: cutter radius is 216 mm; cutter tip thickness is 20mm; and there are 42 cutters on the cutterhead.

In addition, operating data derived from the control system of the machine were recorded in real-time: the rate of penetration ranges from 40~140mm/min, while the range for penetration is 5~25mm/rev.

The curves of predicted and measured total thrust were illustrated in Figure4. The results revealed that the total advancing distance could be divided into two parts. The measured thrust of the first part (from 0~6500m) is low due to the soft rock. However, the total thrust of the second part(from 6500~10000m) is relatively high because of the high uniaxial compressive strength of the rock. The predicted one also has a two-stage trend and shows good agreement of the measured curve.

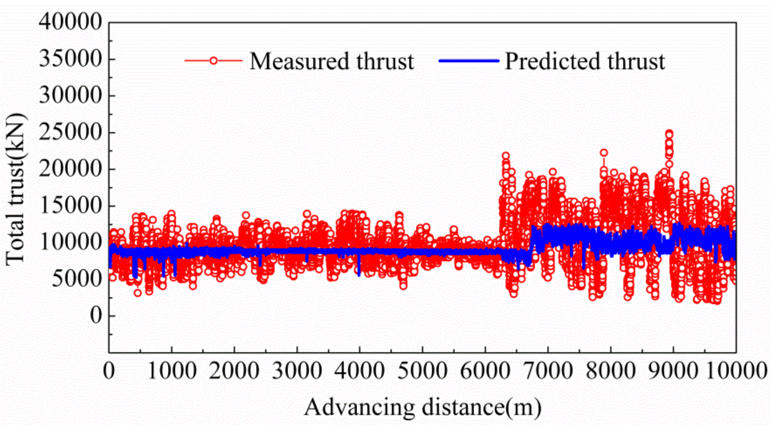

Fig. 4. Comparation between predicted thrust and measured thrust of Yintao project.

Two case studies were presented, and the comparison between the measured curve and the predicted curve indicates that the model could reflect the overall trend of the total thrust force. Since it takes into account the interaction between the ground and the equipment, this prediction is capable of reflecting the influences of geological and operating parameters.

However, the predicted curve was more moderate in contrast with the measured one, this is due to the existence of shear zones ,joints, faults, and other local weakness zones. The excavating equipment will have unstable performances when facing such complicated ground condition. Therefore, more detailed geological information is required for further research of the influences of weakness zones.

4 Conclusions

This paper conducted mechanical analysis and modeling on the total thrust acting on TBMs, and then discussed the relationships between the thrust and the geological, operating, and structural parameters.

Based on the mechanical equilibrium during excavation, several force components acting on the cutterhead, the shield and the subsequent equipment, were fully analyzed. Especially, the force acting on the cutterhead was mainly analyzed. During the progress of excavation, a TBM is affected by the confining pressure as well as geological resistances on the tunneling interface. The paper used infinitesimal body of rock in contact with the arc surface of a cutter to discuss the stress state. According to Mohr-Coulomb criteria, maximum principal stress was calculated, which is the limiting radial stress during rock breaking. Subsequently, mechanical analysis on the interaction between the rock and a cutter was performed. The proposed mechanical formula of the entire cutterhead could reflect influences of geological, operating, and structural parameters. On this basis, a predictive model of the total thrust was set up.

Furthermore, an engineering project was involved to verify and analyze the proposed model. The predicted one shows a good agreement with measured curve, and fluctuates around it. The results indicate that this approximate prediction model takes into account the effects of geological and operating conditions, hence it is able to reflect the overall trend of the total thrust force.

Acknowledgements. This work was supported by National Basic Research Program of China (973 Program, Grant No. 2013CB035402) and National Natural Science Foundation of China (NSFC, Grant Nos. 11127202 and 11302146).

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