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Research on wear prediction of disc cutter based on friction work principle

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A R T I C L E I N F O

A B S T R A C T

As the main rock breaking tool of tunnel boring machine, the wear of disc cutter is affected by geological conditions, equipment factors and tunnelling parameters when it interacts with rock. Because of the complex factors affecting the disc cutter wear, it is difficult to accurately predict the wear of disc cutter. Firstly, the rock breaking mechanism and the force of disc cutter were analyzed, a theoretical prediction model of disc cutter wear is established based on the friction work principle. Then, the parameters in the disc cutter wear prediction model can be determined by simulation and a prediction method of disc cutter wear is proposed. Finally, the wear prediction model of disc cutter is verified by field wear data of disc cutter. The results show that the average error between the predicted value of disc cutter and the actual wear data of construction site is 16.1%. The wear prediction model of disc cutter has high accuracy and adaptability. The research results provide an effective method for wear prediction of disc cutter, which is of great significance and engineering value for cutter replacement and construction management.

Keywords:
tunnel boring machine(TBM)
disc cutter
friction work
wear prediction

1. Introduction

In the tunnelling process of tunnel boring machine (TBM), the wear of disc cutter is one of the most important and inevitable problems. The wear of disc cutter will aggravate the wear and tear of cutter ring, which will reduce the tunnelling efficiency. If the disc cutter is not replaced in time after wear, it will easily lead to the tool damage of the whole cutterhead, which will increase the construction risk and cost. Especially in the river crossing and sea crossing tunnel engineering under complex geological conditions, the disc cutter wear problem is more prominent. Once handled carelessly, it will threaten the safety of life and property. This is also a common construction problem faced by TBM technology (Feng et al.(2016)). At present, tunnel boring machine (TBM) construction mostly relies on experience to judge the opportunity of opening the cabin and changing cutters. However, in the high water pressure cross river and sea tunnel, the frequency of opening cabin and changing cutters are largely limited. Therefore, it is necessary to realize the accurate wear prediction of disc cutter, effectively guide the cutter replacement of TBM and avoid accidents.

In the process of tunnel construction, the disc cutter penetrates into the rock under the action of thrust and torque of cutterhead to complete the rock breaking process. The reason of disc cutter wear is the interaction between disc cutter and rock, which involves complex physical and mechanical mechanism. The wear process of disc cutter is affected by many factors such as geological parameters, tunnelling parameters and equipment parameters. The wear of disc cutter directly affects the efficiency of tunnel excavation. Therefore, it is of great significance to study the wear prediction of disc cutter. In recent years, many scholars have done a lot of research on the wear of disc cutter of TBM. In the aspect of theory, a well-known theoretical approach for disc cutters and performance prediction model are CSM and NTNU (Rostami et al. (1996,2013,1993)). These two prediction models are semi-theoretical models, and derived from a large number of experimental data. Zhaohuang Zhang et al. (2019) put forward a theoretical prediction model of cutter wear by analyzing the movement of cutter in rock breaking process, which was verified by the construction data of Qinling tunnel. The relative errors between cumulatively predicted and measured wear values for nine cutters are larger than 20%, while approximately 76.9% of total cutters have the relative errors less than 20%. However, the applicability of the theoretical model for disc cutter wear prediction needs to be further studied. Comakli et al.(2019) defined the average disc cutter consumption rate as the disc cutter material loss per cubic meter of rock excavated, and studied the relationship between the physical and mechanical properties of low-strength volcanic rocks and the water content of rocks in karpasia, Turkey. It was found that disc cutter wear was directly related to rock strength and rock water content. With the increase of rock strength, the average disc cutter consumption rate decreased. There is a lack of quantitative wear prediction for disc cutters. Hassanpour et al. (2014) carried out statistical analysis by monitoring disc cutter wear, geological parameters and tunnelling parameters to determine the relationship between disc cutter wear and geological parameters. The disc cutter wear prediction model was established based on geological parameters, and verified the correctness of the model through engineering. But the wear prediction model of disc cutter is empirical model, which qualitatively expresses the relationship between cutter wear and geological parameters. Ebrahim et al.(2018) established an empirical formula based on the relationship between rock wear rate index and TBM performance data, and another empirical formula based on laboratory wear test data between disc cutter material and field rock. At the same time, they were integrated into the wear test of small TBM with equal cross-section, so as to put forward a new empirical formula for prediction and provide the most accurate tool change interval length and time. Zhang et al. (2017) studied the wear characteristics of disc cutter of TBM under dry, moist and seawater conditions. A series of wear tests were carried out on the disc cutter performance test-bed, and the wear of disc cutter was the largest under dry conditions, and the smallest in seawater, indicating that wear conditions have a significant impact on the wear behavior of disc cutters. Rong et al. (2019) introduced the wear prediction model of disc cutter based on tunnelling parameters such as cutterhead torque, cutterhead speed and foam flow rate. Combined with actual wear data of disc cutter, the quantitative relationship between cutterhead torque and foam volume and disc cutter wear was obtained. The above three kinds of disc cutter wear prediction models are also obtained through indoor or field test data, not based on the wear mechanism of cutters, and the universality of the models needs further research. Based on the abrasive wear equation and CSM disc cutter force prediction model, Yang Yandong et al. (2015) derived the prediction model of disc cutter wear rate through approximate calculation and mathematical formula, and verified by the actual disc cutter wear data. There is no reliable method to determine the key parameters in the prediction model. Tan Qing et al. (2017) obtained the kinematic equation of disc cutter by analyzing the motion law between disc cutter and cutterhead, established disc cutter wear prediction model combined with abrasive wear theory and mechanical properties of disc cutter in rock breaking. The rock breaking process of disc cutter were programmed and simulated by using Matlab software, and verified correctness of the wear prediction model of disc cutter combined with field disc cutter wear data. However, the error between the simulation results and the measured values is large. Zhou Fuxin et al. (2017) used the multivariate nonlinear regression method to curve fit the tunnelling parameters of TBM. The disc cutter wear prediction model was established, and predicted the disc cutter wear amount by using the tunnelling parameters and driving distance, and detected the correctness of the disc cutter prediction model through mathematical methods. Only tunnelling parameters are considered in this model. The geological conditions and cutters intervals are not considered. Therefore, the model is not applicable when the construction geological parameters change. Considering the influence of tunnelling and geological parameters on disc cutter wear, Yang et al.(2019) put forward the concept of comprehensive wear coefficient of cutter ring, and established a disc cutter wear prediction model. This model was applied to the construction of double shield TBM of water conveyance tunnel in Lanzhou water source construction project, which has better effectiveness than other disc cutter wear prediction models. The key parameter of the model is the comprehensive wear coefficient of the cutter ring, which is affected by many factors and is difficult to be determined. Dongjie Ren et al.(2018) proposed a disc cutter wear prediction model based on the stress analysis and friction energy. The relationships between friction energy during cutting, working status of the machine and the characteristics of the geological conditions were evaluated in this paper, and the wear prediction mode based on friction enegy was applied to two field cases. But the empirical coefficient for energy transfer in the prediction model was determined by the disc cutters wear datas from the fileld. Therefore, the accuracy of the model is limited by the empirical coefficient of energy transfer.

It can be seen from the previous studies that most of the wearing prediction models of disc cutter mainly consider the force of disc cutter, and fail to make a detailed analysis on the mechanism of cutter wear. Only a small number of prediction models are derived from the mechanism of cutter wear, but the combined effect of various wear mechanisms is not fully considered. Therefore, the results of cutter prediction model have a large error with the actual situation, and the engineering application is limited. Therefore, this paper analyzes the rock breaking mechanism of disc cutter from the perspective of energy conservation which combines metal tribology theory, and establishes the wear prediction model of disc cutter based on friction work comprehensively by considering various factors affecting disc cutter wear. The prediction of disc cutter wear is realized through engineering verification, which provides an effective method for the study of disc cutter wear.

2. Wear prediction model of disc cutter based on friction work

The disc cutter is contact with rock directly in the construction process of TBM, resulting in wear of disc cutter ring. Disc cutter ring is a wear and tear part, so it is very important to predict its wear (Zhang et al.2010). In order to accurately predict the disc cutter wear, it is necessary to establish a wear prediction model suitable for engineering application.

2.1. Rock breaking mechanism of disc cutter

In the process of tunnel excavation, the cutter ring penetrates into the rock under the action of thrust and torque of cutterhead. The interaction between rock and cutter will cause the wear of cutter ring while the rock is broken off. At present, the rock breaking process of disc cutter is analyzed by elastic-plastic theory and Hertz contact theory. The schematic diagram of rock breaking mechanism is shown in Fig. 1.

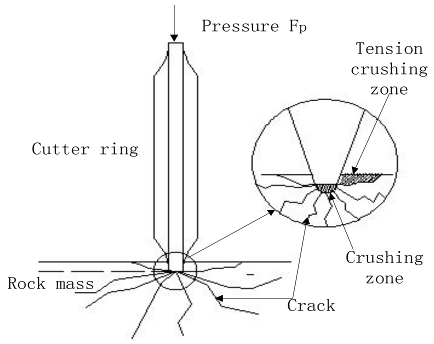

Fig. 1 Rock breaking mechanism of disc cutter

The Fig.1 shows the rock breaking mechanism of the disc cutter is that when the maximum compressive strength of the rock is not enough to resist the pressure form the disc cutter, the rock under the cutter ring will be crushed, and part of the rock will be crushed into powder to form a crescent shaped dense core. The pressure will expand to the surrounding through the dense core, forming radial cracks and lateral cracks. The cracks interact with each other, which makes the rock slag fall off from the rock surface, and the middle crack continues to expand into the rock, completing the rock breaking process. The rock breaking mechanism of disc cutter has a direct influence on establishing force model of disc cutter, which provides theoretical basis for the wear of disc cutter.

2.2. Force analysis of disc cutter

As the main rock breaking tool of TBM, disc cutter is mainly composed of cutter ring, cutter body, end cover and cutter shaft et al. The force of disc cutter during rock breaking is shown in Fig. 2.

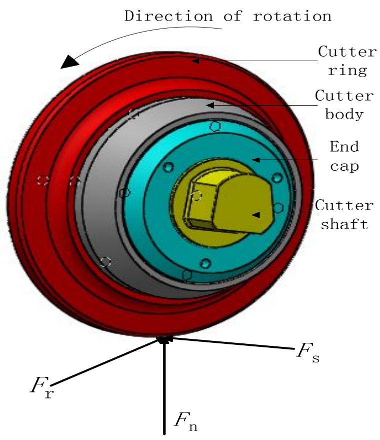

Fig. 2 Sketch of forces acting on disc cutters

Due to the interaction between the cutter ring and the rock in the process of rock breaking, forces with three directions are applied on the disc cutter. The first is vertical force of disc cutter, which points to the face of the rock and is provided by the thrust of the cutterhead. The second is tangential force points to the tangential direction of the disc cutter and is provided by the torque of the cutterhead. The third is lateral force generated by the squeezing force of the disc cutter on the rock and the centrifugal force of the cutterhead rotation, pointing to the center of the cutterhead. They are marked as F_n, F_r and F_s respectively in the Fig.2. The lateral force numerical order of magnitude is small, and the effect of lateral force on disc cutter is generally ignored (Tan et al. 2018).

For the rock breaking mechanical model of disc cutter, the scholars have carried out a lot of research. At present, the CSM disc cutter stress prediction model proposed by Corollado Mining Institute is widely used (Rostami et al.1996). The CSM disc cutter force prediction model is derived from the summary of a large number of engineering data, which is mainly used to predict the tunnelling performance of TBM. The CSM model has been verified by a large number of experiments on the linear cutting experimental platform. It can be used to estimate the resultant force of disc cutter in the working process. The CSM model is as follows,

$$\begin{cases} F_t = \dfrac{P^0 \phi RT}{1+\psi} \\ \phi = \arccos(\dfrac{R-h}{R}) \\ P^0 = C\sqrt[3]{\dfrac{S}{\phi\sqrt{RT}}\sigma_c^2\sigma_t} \end{cases} \quad (1)$$

Where, F_t is the resultant force of disc cutter (kN), R is the radius of disc cutter (mm), T is the width of disc cutter edge (mm), the ψ is the pressure distribution coefficient of tool tip, which decreases with the increase of blade width, and ψ= 0.2～－0.2, φ is the contact angle between the disc cutter blade and the rock (rad), the h is disc cutter penetration (mm), P^0 is the pressure in the rock fracture zone, which is related to rock strength, disc cutter geometry, penetration and cutter spacing,($P^o = f(\sigma_t, \sigma_c, T, R, \phi, S)$). C is a constant similar to rock contact angle φ, with the value of 2.12; s is the cutter spacing of disc cutter (mm), σ_c is the uniaxial compressive strength of rock, σ_t is the tensile strength of rock. The pressure distribution of rock under the action of disc cutter is shown in Fig. 3 (a). The vertical force F_n and tangential force F_r of disc cutter are as follows,

$$F_n = F_t\cos\frac{\phi}{2}, \quad F_r = F_t\, sin\frac{\phi}{2} \quad (2)$$

2.3. Establishment of wear prediction model for disc cutter

The movement of rock breaking point on the disc cutter is a complex movement when the disc cutter breaks rock. The disc cutter is driven by the thrust and torque provided by the cutterhead, which makes it revolve around the center of the cutterhead. At the same time, the disc cutter rotates along its own cutter axis under the friction of hard materials such as rocks. In the process of interaction between disc cutter and rock, there are rolling friction and sliding friction. When the disc cutter is in pure rolling friction, the wear amount of disc cutter is small, which can be ignored. Therefore, it is considered that the wear amount of disc cutter is caused by the relative sliding friction between disc cutter and rock (Yang et al. 2015; Zhu et al. 2007). The slip amount of disc cutter is one of the key factors of cutter wear prediction when the disc cutter breaking rock .

In the process of rock breaking, the disc cutter is not only subject to relative movement, but also affected by the embroil motion. So, the slip arc length of rock breaking point P of the cutter ring is a three-dimensional curve (Zhang et al.2007). The Fig. 3 shows the rock breaking process of the disc cutter on the cutterhead. Fig. 3 (a) shows the disc cutter rotates the angle of φ at the angular velocity of ω, and the relative displacement is $\overrightarrow{S_{pr}}$, when the disc cutter breaking rock. Fig. 3 (b) shows the implicated motion of the disc cutter on the cutterhead. The disc cutter rotates θ at the angular velocity of W_d, and the implicated displacement is $\overrightarrow{S_{pl}}$. According to the coordinate relation, the displacement of rock breaking point P can be projected on each coordinate as follows:

$$\begin{cases} x_p = \dfrac{R^2}{R_c}(1-\cos\phi) = \dfrac{R}{R_c}h \\ y_p = R\arccos\ (\dfrac{R-h}{R_c} - \sqrt{2R\ h - h^2}) \\ z_p = R(1-\cos\phi) = h \end{cases} \quad (3)$$

Where, R_c is the installation radius of the disc cutter on the cutterhead. According to the reference (Zhang et al.1998), the analytical solution of sliding distance S_P of any rock breaking point P on the cutting edge for each turn of positive disc cutter is as follows:

$$S_p = \int_s ds = \int_s \sqrt{x_p^2 + y_p^2 + z_p^2}\, dp \quad (4)$$

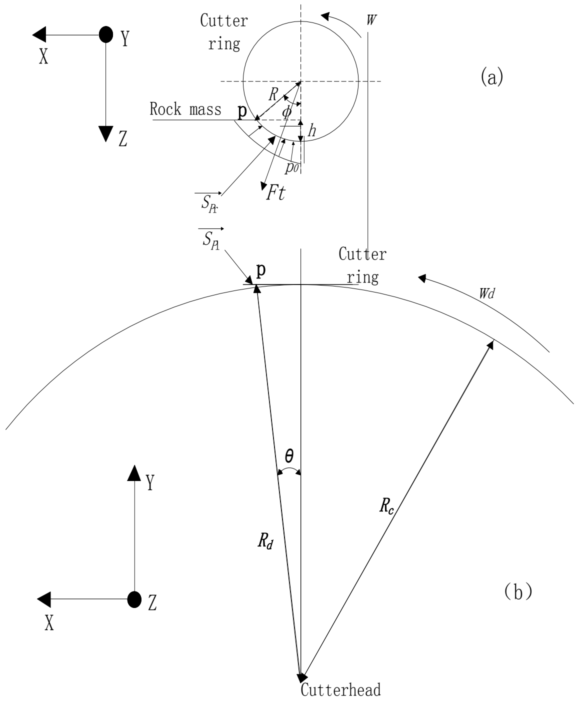

Fig. 3 Schematic diagram of rock breaking process of cutter on cutterhead

According to the energy wear theory proposed by Fleisher, the wear reason in the process of friction between two objects is that the energy accumulation of the object reaches a certain degree and the loss of shedding occurs. The wear of disc cutter is mainly abrasive wear. The material molecules of cutter ring do work to counteract the sliding friction work between disc cutter and rock, resulting in the wear of cutter ring material. If the process of rock breaking by disc cutter is infinitesimalized, and it is assumed that the work dW per unit friction force is proportional to the unit wear volume dV, the equation (5) is satisfied for any element region.

$$\mathrm{d}V = \eta \mathrm{d}W \quad (5)$$

Where, η is the wear coefficient (m^3/J) and represents the wear amount generated by unit friction work.

Since the sliding friction force of disc cutter in rock breaking is far greater than that of rolling friction force, sliding friction is the main factor leading to disc cutter wear. Ignoring the rolling friction force of disc cutter, only the sliding friction force is considered as work. The formula (5) can be written as follows,

$$\mathrm{d}W = F_f v \mathrm{d}t \quad (6)$$

Where, F_f is the friction force in the unit area(N), $F_f = \mu F_\mathrm{n}$, F_n is the positive pressure of rock on the cutter ring (N), μ is the friction coefficient. v is the velocity of rock particles relative to the cutter ring in the unit area (m/s), dt is the time step (s).

The friction work in each element is calculated as the product of the force in the element and the friction distance by divided the process of rock breaking into several parts. When the disc cutter rotates one circle, the relative displacement between the rock breaking point and the rock is as follows,

$$L_p = R\,\phi \approx \sqrt{D\,h} \quad (7)$$

Where, D is the diameter of disc cutter (mm).

The ratio of cutter slip distance to total contact distance is defined as slip ratio λ，

$$\lambda = S_p / L_p \quad (8)$$

When the disc cutter is in normal wear, the slip ratio is small. When the disc cutter has uneven wear, the slip ratio is 1, and the wear of disc cutter will increase greatly in this conditions. Therefore, it is necessary to avoid and reduce the abnormal wear of disc cutter caused by eccentric wear. When the friction work of each unit is superimposed, the work done by the friction force per revolution of the disc cutter is as follows:

$$W_p = FS_p = 2\mu F_n \lambda R_p \pi \quad (9)$$

Considering the interaction between disc cutter and rock, the wear volume of disc cutter and the characteristics of rock can be combined to calculate the wear volume V_p of disc cutter per revolution is,

$$V_p = IW_p \quad (10)$$

Where, I is the energy wear rate, it is the wear volume amount of disc cutter material caused by unit friction work. The energy wear rate I can be obtained by the steel needle made of disc cutter material and rock abrasion test of relevant rock materials on site. The friction coefficient between the cutter and rock and the energy wear rate I of the cutter material can be measured by using the rock abrasivity experimental equipment, as shown in Fig. 4. The friction coefficient between steel needle and granite is 0.4 and the energy wear rate of disc cutter material is 1.53×10^{-4} mm^3/J by the experimental results.

Fig. 4 Rock erosion experiment

Assuming that the wear state of disc cutter remains unchanged, the friction work in a unit can be extended to the whole process of tunnel construction through the above motion law of disc cutter. By establishing the mathematical relationship between the wear volume of disc cutter and the friction work of the whole project, the total mileage of tunnel construction is L (m), so the radial wear amount X_{p} of disc cutter is calculated as follows:

$$X_p = \frac{V_{\mathrm{p}} L}{2\pi RT\ h} \times \frac{R_{\mathrm{c}}}{R} = \frac{\lambda \mu F_n I R_{\mathrm{c}} L}{TR\ h} \tag{11}$$

Equation (11) can be used to calculate and predict the disc cutter wear, but the first thing to complete is to determine the parameters in the formula. We can get the parameters of the energy wear rate I and the friction coefficient by using the laboratory test of the disc cutter and rock . According to the record and statistics of the tunnelling parameters and disc cutter, the structural parameters of the cutter can be obtained, such as the radius of the disc cutter ring R, the installation radius of the disc cutter R_{c}, the total tunnelling mileage L, the width of the disc cutter tip T and the penetration h. However, the vertical force F_{n}, wear volume V_{p} and slippage S_{p} of disc cutter can not be obtained directly, so it is necessary to use other methods to determine these parameters.

3. Rock breaking simulation and parameter determination of disc cutter

3.1. Establishment of rock breaking simulation model of disc cutter

The undetermined parameters in the theoretical model of disc cutter wear prediction can be obtained by experiment or simulation. Compared with the experiment, the cost of rock breaking simulation of disc cutter is low and the simulation accuracy is high, the finite element software is used to simulate the rock breaking process of disc cutter. When the finite element method is used to simulate the process of rock breaking by disc cutter, it is assumed that the excavation stratum is uniform hard rock ground and there is no discontinuity problem such as fracture zone. In this case, the finite element method is relatively simple and the simulation results are more reliable. If there are discontinuous problems such as broken zone and uneven rock in the process of rock breaking by disc cutter, other numerical simulation methods can be adopted, such as peridynamics (Wang et al.(2016,2018)), general particle dynamics(Bi et al.(2016); Zhou et al.(2015)) and the extended finite element method(Zhou et al.(2012)). In this paper, a 19 inch disc cutter is used. Considering that only the disc cutter ring is directly contacted with the rock in the process of rock breaking, the disc cutter model is established only with the cutter ring part. The arc diameter of the edge of the disc cutter model is 16 mm, the width of the cutter ring tip is 19 mm, and the three-dimensional model size of the rock is 150 mm × 75 mm × 250 mm (length× width× height). The rock breaking model of disc cutter is established as shown in Fig. 5.

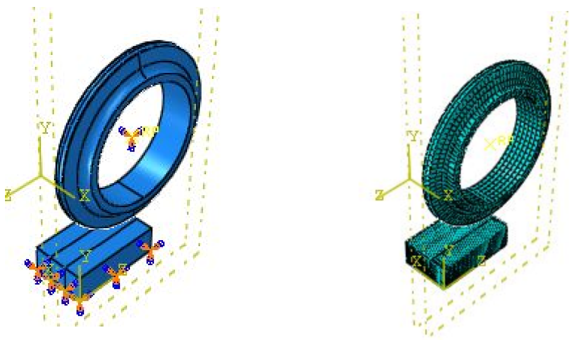

Fig. 5 Rock-breaking simulation model of disc cutter

In rock breaking model of disc cutter, the rock material adopt Drucker-Prager criterion for simulate rock failure. Meanwhile, according to actual excavation engineering data, parameters of rock model are set as shown in Table 1.

Table 1 Mechanical parameters of rock materials

Elastic Modulus	Poisson's Ratio	Compressive Strength	Tensile Strength	Shear Strength	Density (kg/mm)

(MPa)		(MPa)	(MPa)	(MPa)	
47.6	0.22	120.4	16.4	21.4	2.58

According to the actual excavation data of a cross sea tunnel project, the parameters in the simulation model are set. The rotating speed of cutterhead is 8 r/min, the installation radius of disc cutter is 0.919 m on cutterhead, the penetration is taken as the average value of the actual project, the penetration is set 7 mm, and the friction coefficient is 0.4. The load and boundary conditions are set as follows: fix three surfaces of rock in displacement, set 7 mm displacement along the negative direction of Y-axis for disc cutter; set 769 mm/s translation speed along X-axis direction and 3.19 rad/s rotation speed around X-axis for disc cutter.

3.2. Rock breaking simulation results analysis of disc cutter

Submit the disc cutter rock breaking operation in the operation column of the software. After the operation is completed, click the visualization module in the menu bar. In this module, the generated format is ODB visualization file. The results of this file will be imported into Abaqus post processor. Considering the influence of penetration on the force and friction work of disc cutter, setting different penetration parameters can obtain the force and friction work of disc cutter.

3.2.1. Force analysis of disc cutter rock breaking simulation

The force of disc cutter can be obtained through the post-processing of rock breaking simulation of disc cutter. Because the lateral force of disc cutter is small and can be ignored, the force of disc cutter can be divided into vertical force and tangential force. The Fig. 6 shows the variation of disc cutter vertical force and tangential force with time when the penetration is 7 mm.

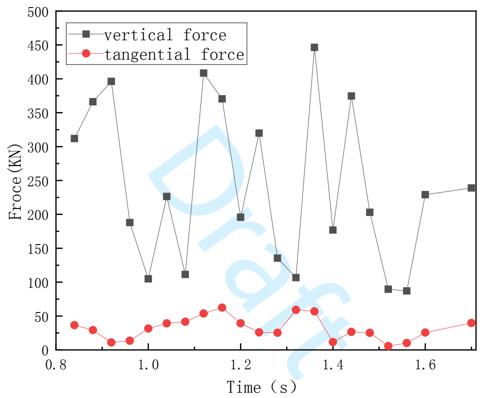

Fig. 6 Force curve of disc cutter

It can be seen from Fig. 6 that the force of disc cutter is alternating because the rock is discontinuous medium. The vertical force and tangential force of disc cutter change with time, but both of them fluctuate around a value. The average value of vertical force and tangential force of disc cutter is 232.7 kN and 26.8 kN respectively when the penetration of disc cutter is 7 mm.

Due to the continuous change of geological conditions in the actual tunnelling process, geological conditions have a direct impact on the setting of cutter penetration. Different penetration parameters are set to simulate rock breaking by disc cutter, and the average values of vertical force and tangential force under different penetration are calculated. At the same time, the vertical force and tangential force of CSM disc cutter force prediction model under different penetration are compared, as shown in Fig. 7.

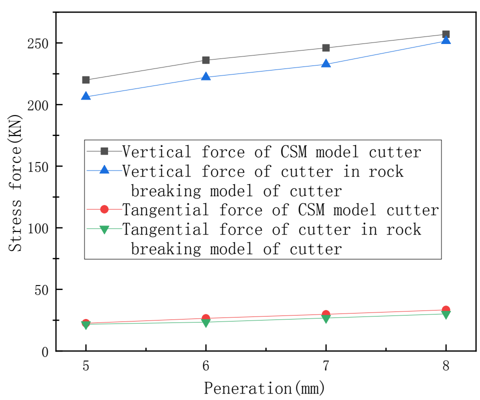

Fig. 7 Force comparison between CSM model and rock breaking simulation model of disc cutter

It can be seen from Fig. 7 that the force of disc cutter increases with the increases of disc cutters penetration, and the change trend of theoretical value calculated by CSM model of disc cutter is consistent with that calculated by simulation model. The average relative errors of vertical force and tangential force are 4% and 8%, respectively. The reason for the error is that the calculated value of CSM model is based on a large number of experimental data of rock breaking by cutters, and the anisotropy of rock in geological conditions will cause certain error. In the simulation of disc cutter breaking rock, the numerical value is obtained under ideal condition, the failure criterion of rock has a certain range and is related to the mesh division of simulation model.

3.2.2. Friction work of disc cutter in rock breaking

By analyzing the rock breaking mechanism of disc cutter, it is found that there is no sliding phenomenon when disc cutter is pressed into rock vertically, and the dissipation of friction work is very small. When the disc cutter starts to rotate, although the sliding part accounts for a small proportion, it will produce a great amount of friction work (Geng et al. 2018; Wang et al. 2012). In the post-processing interface, the ODB file of the rock breaking simulation model of the disc cutter with a penetration of 7 mm is derived, in which the frictional dispersion (friction work consumption) is selected. The friction work consumed by the disc cutter for rock breaking with a penetration of 7 mm is shown in the Fig. 8.

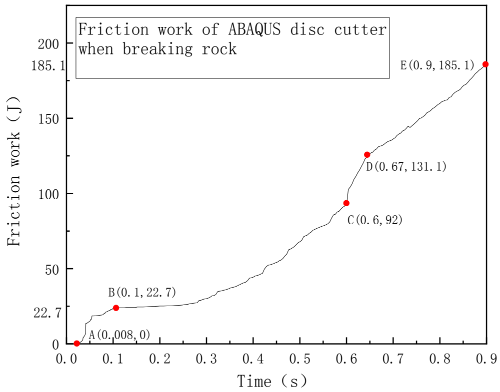

Fig. 8 Friction work curve of disc cutter with time

It can be seen from Fig. 8 that the disc cutter slides relative to the rock during the rock breaking process, and the friction force between the cutter and the rock does work. The sliding distance between cutters and rocks increases with the increase of rock breaking time, and the friction work of disc cutters increases. The action time of disc cutter friction work is 0.1 ~ 0.9 s during rock breaking. The friction work of disc cutter is 22.7 J when it cuts into the rock vertically in 0 ~ 0.1 s. After that, the disc cutter began to rotate, and the friction work was 185.1 J after 0.9 s of rock breaking. The simulation lasted for 0.9 s, and the friction work consumed by disc cutter in this time interval is 162.4 J, which provides a theoretical basis for the establishment of theoretical model for disc cutter wear prediction.

3.3. Parameter determination of disc cutter wear prediction model

Since the vertical force F_n, wear volume V_p and slip S_p cannot be obtained directly in the theoretical model of disc cutter wear prediction, the force and friction work of disc cutter need to be obtained by rock breaking simulation process of disc cutter. Then, according to the penetration of disc cutter is 7 mm, the average vertical force of disc cutter is 232.7 kN, the friction coefficient is 0.4 and formula (9) is used to calculate the slip value s = 1.74 mm. In the same way, the slip of disc cutter under different penetration can be obtained, and the slip of disc cutter corresponding to different penetration are listed as the Table 2.

Table 2 Slip of cutter at different penetrations

Penetration of disc cutter(mm)	Slip of disc cutter(mm)
5	1.11
6	1.4
7	1.74
8	2.3

It can be seen from table 2 that the slippage of disc cutter increases with the increase of penetration, but the relationship between them is not linear. When the penetration of disc cutter is small, the increase of slip is small with the increase of penetration. However, when the penetration of disc cutter is large, the increase range of slip is large with the increase of penetration. The calculation of slip provides a theoretical basis for the establishment of wear prediction model of disc cutter.

According to formula (10), the wear volume of disc cutter with different penetration can be calculated. According to the excavation data, the total tunnelling mileage of TBM is 1221 m. The radial wear length of disc cutter is calculated by formula (11), and then the wear amount of the disc cutter is calculated through the proportional relationship when the cutterhead rotates for one cycle. In this paper, the disc cutter is located at the cutterhead radius of 919 mm, and the wear path in the simulation is 250 mm. When the cutterhead rotates for one circle, the wear amount of disc cutter under different penetration is obtained by proportional relationship, and the radial wear length of disc cutter can be calculated, as shown in Table 3.

Penetration (mm)	Friction Work (J)	Wear Volume (mm^3)	Radial Wear Length (mm)

Table 3 Friction work, wear volume and radial length of cutter at different penetrations

5	89.8	3.16x10^{-1}	10.34
6	125.8	4.4x10^{-1}	11.83
7	162.4	5.72x10^{-1}	13.21
8	226.7	7.99x10^{-1}	16.12

4. Engineering verification of disc cutter wear prediction model

Through the rock breaking simulation of disc cutter, the stress and friction work of disc cutter under different penetration can be obtained, and then the parameters in the prediction model of disc cutter wear can be determined. Combined with the geological conditions, equipment parameters and tunnelling parameters in the actual construction process, the theoretical model of disc cutter wear prediction is applied to practical engineering. Through the prediction model, the wear prediction of frontal disc cutters on the whole cutterhead are carried out, and the correctness of the prediction model is verified by comparing the wear data of disc cutters in the actual construction process.

4.1 Wear analysis of disc cutter

Based on a cross sea tunnel project of Qingdao Metro, the engineering geological profile of the project is shown in Fig. 9. According to the drilling survey of tunnel geology, the engineering geology is mainly composed of granite, and the distribution of granite accounts for more than 90%. Due to the shallow buried depth of the line, large fluctuation of bedrock surface and great difference in engineering properties of weathered rock, the surrounding rock grade of the tunnel is grade II ~ VI, and the surrounding rock classification is mainly grade II ~ IV. The integrity of the rock is good and there are some broken zones. The uniaxial compressive strength of the rock is between 11.41 MPa and 154.3 MPa, of which about 50 MPa is the main on. The rock sampling samples for tunnel geological investigation are shown in Fig. 10.

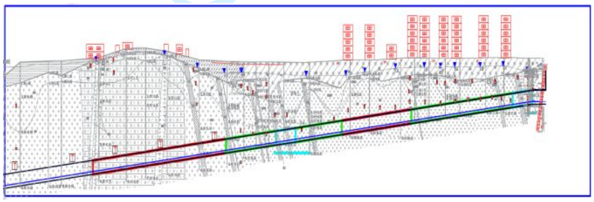

Fig. 9 The profile of engineering geologica
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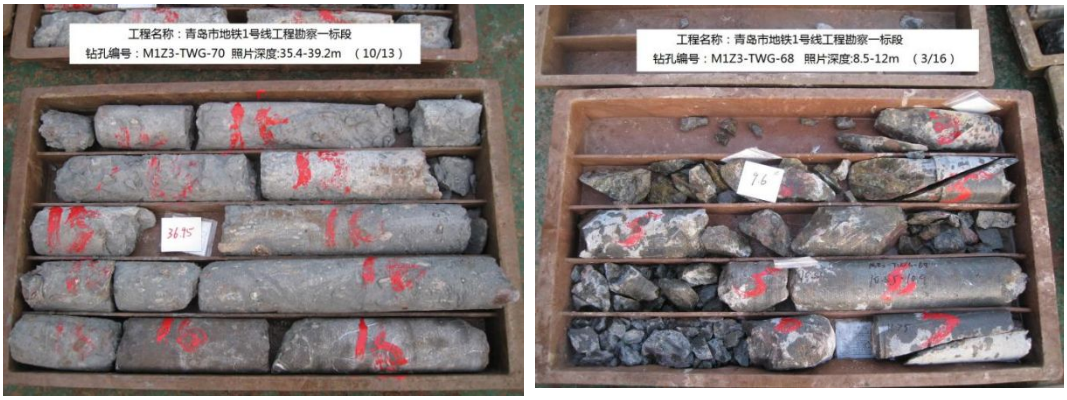

(a) Samples of relatively complete rock mass (b) Rock samples from fractured zones

Fig. 10 Engineering geological survey sample

The cutterhead is shown in Fig. 11. The 19 inch standard disc cutter is selected on the cutterhead. The diameter of the cutter is 482.5mm, and the width of the cutter tip is 19mm. The No. 1 ~ 8 Cutter on the cutterhead of TBM is central disc cutter, the No. 9 ~ 28 cutter is frontal disc cutter, and the No. 29 ~ 41 cutter is edge disc cutter, the spacing of frontal cutter is 82 mm, as shown in the table 4. The penetration range of TBM is 5 ~ 8 mm in excavation of tunnel.

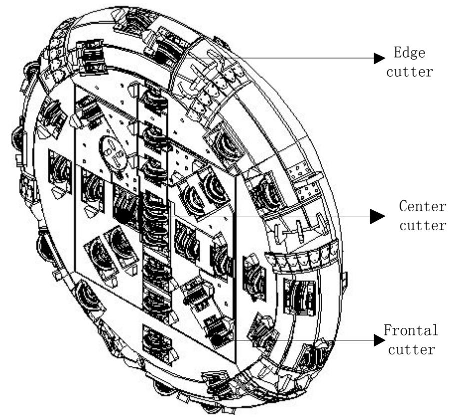

Fig. 11 The drawing of Cutterhead

Table 4 The disc cutter layout on the cutterhead

Cutter type	Cutter number	Radius\(mm)	Space\(mm)	Cutter type	Cutter number	Radius\(mm)	Space\(mm)	Cutter type	Cutter number	Radius\(mm)	Space\(mm)
Center cutter	1	62	99	Frontal cutter	15	1329	82	Edge cutter	29	2476.7	81.7
	2	161	99	Frontal cutter	16	1411	82		30	2557.7	81
	3	260	99		17	1493	82		31	2637.3	79.6
	4	359	99		18	1575	82		32	2714.8	77.5
	5	458	99		19	1657	82		33	2789.4	74.6
	6	557	99		20	1739	82		34	2860.1	70.7
	7	656	99		21	1821	82		35	2925.9	65.9
	8	755	99		22	1903	82		36	2985.8	59.9
Frontal cutter	9	837	82		23	1985	82		37	3038.5	52.7
	10	919	82		24	2067	82		38	3082.7	44.2
	11	1001	82		25	2149	82		39	3117	34.4
	12	1083	82		26	2231	82		40	3140	23
	13	1165	82		27	2313	82		41	3150	10
	14	1247	82		28	2395	82				

Through the measurement and statistics of disc cutter wear data, the cutter number, size, installation radius and wear amount of disc cutter are recorded. Considering that the cutter No. 9 ~ 28 is a frontal disc cutter and the radius of the cutter ring and the width of the blade are the same. Therefore, the corresponding relationship histogram between disc cutter number and wear amount is established, as shown in Fig. 12.

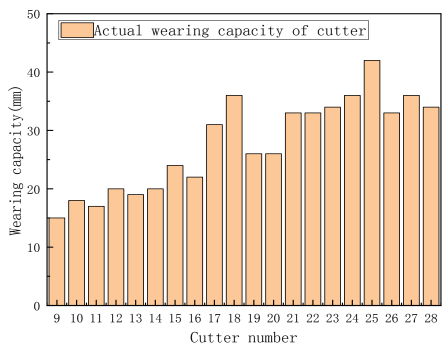

Fig. 12 Bar chart of cutter number and wear of disc cutter

As shown in Fig. 12, it can be seen that the relationship between disc cutter number and wear amount is not a simple linear relationship. The SPSS software is used to fit the above data. The fitting curve equation between the disc cutter number and the wear amount is,

$$y = 2.535 \times x^{0.821} \quad (12)$$

With the increase of disc cutter number, the wear of disc cutter is also increasing, but the increasing range is also decreasing. The wear amount of the cutter can be determined by the known cutter number, and compared with the results calculated by the disc cutter wear prediction model.

4.2 Engineering verification

According to the friction work obtained from the simulation of rock breaking by disc cutter, the wear amount of disc cutter under different penetration can be calculated by using the wear prediction model of disc cutter, and then compared with the actual wear amount of the disc cutter, the engineering verification is carried out, as shown in Fig. 13.

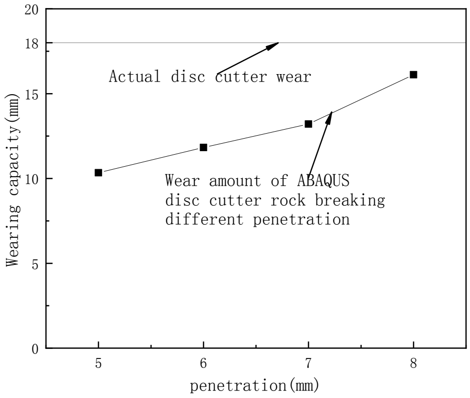

Fig.13 Comparison between actual wear and simulation calculation of disc cutter

Since the penetration of the disc cutter is set at 5 ~ 8 mm according to geological conditions and other factors, the actual wear amount of the disc cutter in the figure 13 is the statistical value in the excavation section. It can be seen from Fig. 13 that the wear amount of disc cutter calculated by the disc cutter wear prediction model increases with the increase of penetration, and the increase range of disc cutter wear increases with the increase of penetration.

The wear prediction of disc cutter is extended from a single disc cutter to all front cutters on the cutterhead. Due to the fact that the TBM is driven at a penetration of 7 mm under most working conditions in the field construction, the wear prediction model of disc cutter is used to calculate the wear of all front disc cutters on the cutterhead under the condition of penetration of 7 mm. The comparison with the actual disc cutter wear data verifies the correctness of the disc cutter wear prediction model. The Fig. 14 shows the comparison between the actual wear amount and the simulated wear amount of the disc cutter when the penetration of disc cutter is 7 mm.

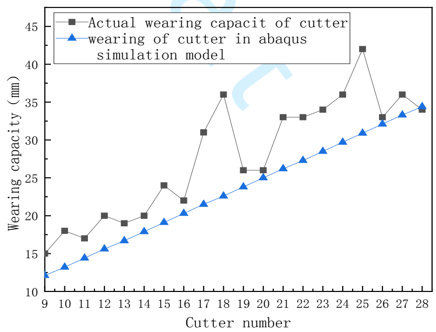

Fig. 14 Comparison of actual and simulated wear of all cutters

It can be seen from Figure 14 that when the penetration of all frontal cutters on the cutterhead is 7 mm, the simulated wear amount increases with the increase of cutter number, while the actual wear amount of cutters gradually increases with the increase of cutter number. The actual cutter wear shows a fluctuating upward trend. The average relative error is 16.1%, which can verify the correctness of the disc cutter wear prediction model. The main reasons for the error between the prediction model and the actual wear amount are as follows: (1) In the actual engineering process, the stratum excavated by TBM is always changing, and the energy wear rate of different strata is different, which will lead to the error with the simulation results. (2) When different TBM operators or face different strata, the tunnelling parameters are usually adjusted to deal with the stratum changes, and the adjustment of disc cutter penetration or other tunnelling parameters will also lead to errors. (3) The cutter is an ideal uniform wear process in the process of rock breaking simulation. In practical engineering, there are also abnormal wear such as chipping edge and eccentric wear in addition to uniform wear. Abnormal wear will aggravate the wear failure process of the cutter ring, resulting in the actual wear amount larger than the predicted wear amount.

5. Conclusion

(1) The wear prediction model of disc cutter based on the principle of friction work is established. Based on the analysis of rock breaking mechanism and force of disc cutter, a theoretical model of disc cutter wear prediction is derived based on the work and energy law. The model takes into account the geological conditions, equipment parameters and tunnelling parameters in the actual rock breaking process. Compared with the previous prediction model, the model has more practical value in engineering.

(2) The parameters in the theoretical model of disc cutter wear prediction are determined by using the finite element simulation analysis method. Based on the rock breaking simulation model of disc cutter, the key parameters such as vertical force F_n, wear volume V_p and slip S_p are

determined, which provides an effective method for analyzing the wear prediction of disc cutter.

(3) The correctness of the wear prediction model of disc cutter is verified through the experimental data of the project site. The wear data of cutter in engineering field is compared with the predicted value of cutter wear, the actual wear of the cutter is greater than the predicted wear of the cutter. The average relative error between the predicted value of the model and the measured wear data is about 16%, which verifies the accuracy of the model. Whether the prediction model is suitable for center cutter and edge cutter needs further verification. The research results provide a scientific method for wear prediction of disc cutter, which has important scientific significance and engineering value for guiding disc cutter replacement and ensuring the safety construction of tunnel.

Conflicts of interest

The authors wish to confirm that there are no known conflicts of interests associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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