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Research on mechanical behavior of rock breaking of abnormal cutter based on PFC numerical simulation

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Abstract: *Cutter wear is an important factor that restricts construction efficiency and cost in TBM tunneling, and abnormal cutter damage will even cause TBM jamming, seriously affecting the construction schedule. Therefore, using PFC particles flow numerical simulation method, two simulation schemes which will possibly cause cutter abnormal damage are set up, researching the mechanics behavior and efficiency of rock breaking. Otherwise, the influence of penetration, rock mass strength and parameters of the cutter itself on cutter force is also analyzed, and the corresponding engineering suggestions are provided in this article.*

Keywords: *TBM cutter; abnormal damage; cutter force; PFC; numerical simulation*

1. Introduction

Because of its advantages of high safety and fast construction speed, Tunnel boring machine (TBM) has been increasingly applied to the construction of highway, railway and water tunnel. However, the complicated geological conditions in the construction process also bring great challenges to the excavation of TBM. Among them, the cost of TBM cutter is huge, and abnormal damage occurs from time to time, which will lead to low excavation efficiency and increased project cost. For example, in the deep buried long tunnel of Qinling in Shanxi province, after the TBM encounters the high abradability stratum, the cutter is seriously worn, which affects the construction progress [1].

Therefore, by studying the interaction law between cutter and rock mass, the mechanism of cutter wear and even abnormal damage is revealed, thus establishing an early warning model of cutter wear prediction and cutter damage, which is conducive to reducing cutter loss and improving tunneling efficiency, and will have certain guiding significance for engineering practice. Previous scholars have studied the normal wear of cutter, and Rabinowicz (1961) [2] proposed a two-dimensional cutter wear theoretical model of abrasive wear mechanism; Lin et al. (2017) [3] used the cutter through different heat treatment processes to carry out the wear test. It is proposed that in the process of breaking rock with different materials of cutter, the forms of abrasive wear of cutter are also different. J. Hassanpour et al. (2014) [4] established an empirical formula of Vickers hardness, uniaxial compressive strength and cutter wear by using regression analysis method based on the engineering data of Karaj water delivery tunnel in Iran, and it can be used to predict cutter wear in pyroclastic rocks and mafic igneous rocks. Liu Quansheng et al. (2017) [5] developed an empirical model for predicting cutter life in granite, revealing the relationship between 20-inch cutter wear and rock abrasivity and strength.

In addition, partial grinding of cutter often occurs under the geological condition of alternating soft and hard. Due to the partial load of the cutter, the inner force of blade wheel is increased, so as to produce the situation of unilateral partial load force wear [6]. Blade wheel cracking is mostly due to improper material selection and heat treatment of blade wheel, blade wheel local overload and impact fatigue fracture; Blade wheel loosening is mostly due to poor welding reinforcement or improper use of cutter closing ring; the damage of the cutter bearing is mostly due to the sealing failure of the cutter bearing ring closing ring or the severe overload of the cutter [7]. The cutter adjustment (the disc cutter in the Edge area is switched to the internal area for use, etc.) increases the height difference between adjacent cutter, making the stress distribution uneven and aggravating the wear of Cutter [8]. In addition, due to the fact that the cutting cutter fails to discharge the cuttings in time after being broken at one time, it falls between the cutting cutter plate and the excavation surface, causing the cutting cutter to break the scattered cuttings twice or more times, cutter is easily damaged [9].

It can be seen from this that there are many researches on the normal wear of cutter by predecessors,

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but most of the researches on abnormal damage of cutter are based on the regular summary of field engineering conditions, however, there are few studies on abnormal wear through rock breaking mechanism. Therefore, this paper uses the numerical simulation software of PFC to establish the numerical model of the interaction between TBM cutter and rocks, and sets up two test schemes that are easy to cause abnormal damage to cutter. The mechanical characteristics of the interaction between cutter and rock and the law of crack propagation are analyzed in order to provide some references for the study of abnormal damage of TBM cutter.

2. Particle flow code method and test preparation

2.1 Advantages of particle flow code method

In recent years, numerical simulation methods have been widely used in the field of TBM tunnels, especially in the research on the mechanism and phenomenon of rock breaking in TBM cutter. However, compared with the conventional finite element method, finite difference method and block discrete element method, particle flow code method software (PFC) is based on Newton's second law and the relationship between force and displacement, and it establishes the mechanical properties between particles, which can better simulate the mechanical properties of rock itself, and it has advantages in analyzing the failure phenomena of discontinuous media such as cracking and separation of rock and soil mass. Huang Haiying et al. (2012) [10] divided TBM rock breaking into two processes: penetration and cutting, and studied the law of crack propagation in plastic zone under the contact of surrounding pressure on cutter rock. Moon (2012), Xia (2017) et al. [11, 12] also adopted the particle flow code method to study the relationship between the ratio of cutter spacing and penetration and the specific energy of rock fragmentation.

2.2 Calibration of rock microscopic parameters

Through the simulation of the actual cutter rock breaking process with PFC, the basic properties and contact properties of rock particles need to be determined first. The macroscopic physical and mechanical properties of rocks are determined by the properties of particles and the interaction between particles in PFC. The microscopic parameters of particles include tensile strength, cohesion, normal/tangential stiffness ratio, elastic modulus, etc. The contact model between particles built in the PFC includes linear-connection model, parallel-bonding model and flat-joint model, among which the flat joint connection model was proposed in Potyondy, the physical model is shown in Fig. 1 [13].

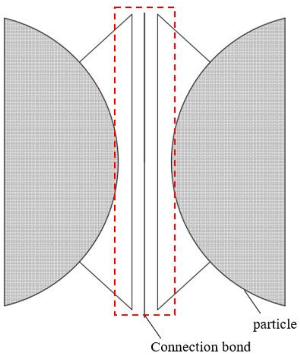

Figure 1: Flat-joint contact model

In the flat-joint model, there is a set of flat connection bonds between two adjacent particles, which can bear the normal force, tangential force and moment. The connecting key complies with the maximum tensile stress criterion and the Moore-Coulomb criterion respectively in the normal direction and tangential direction. When one of them is met, it will produce fracture, and particles will move freely from the matrix, as a result, rocks are damaged. This contact model can improve the problems existing in the parallel bonding model that the ratio of compressive strength to tensile strength is too high and the internal friction angle is too low [14].

In this paper, two groups of rock conditions with macroscopic rock strength of 60MPa and 150MPa are calibrated using flat-joint model through the numerical simulation tests of uniaxial compression and Brazilian splitting, and the key microscopic parameters are shown in Table 1.

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2.3 Cutter model simplification

In the study of TBM cutter rock breaking, scholars such as Rostami and Ozdemir [15] in Colorado Institute of Mining proposed CSM models based on a large number of linear cutting tests and theoretical calculations, and now it has become a classical theoretical model in this field. The model is shown in Fig. 2.

In PFC2D, the wall unit can be used to simplify the cutter model. In the process of cutting, rock particles are broken with the fracture of contact bonds, however, the cutter itself will not deform. At the same time, the program will record the normal force and rolling force of the cutter in contact with the rock, as well as the stress of the cutter and the rock in the whole process.

Table 1: The key microscopic parameters of the rock model

Macroscopic parameters	Microscopic parameters					
UCS (MPa)	Elastic modulus (GPa)	Tensile strength (MPa)	Cohesion (MPa)	Inner friction degree (°)	Normal/tangential stiffness ratio	Friction coefficient
60	0.1	0.3	1.5	8	1	0.3
150	0.2	0.5	4	8	1	0.4

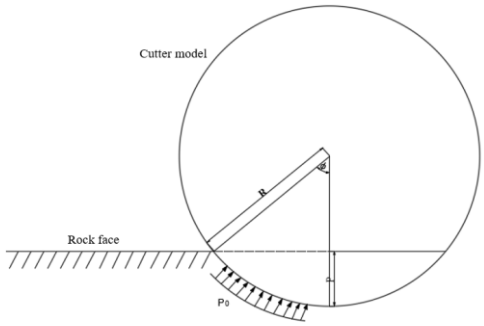

Figure 2: CSM model

3. Test schemes and result analysis

In this paper, two test schemes are designed in the project, researching the mechanical change characteristics of cutter and the development law of rock breaking cracks in two conditions including cutter under the condition that the existing minor damage and the adjacent cutter have formed the position height difference due to wear.

3.1 Simulation of rock breaking with cutter partial grinding

In this paper, Cutter rolling program is compiled to achieve the effect that different parts of the same cutter can cut rock. Take the rock breaking process of partial grinding 5mm cutter as an example, as shown in Fig. 3.

The history Command built in the PFC can be used to record the instantaneous force of cutter rock breaking. Therefore, during the complete and partial grinding cutter rock breaking process, the changes of normal force and rolling force on cutter are shown in Fig. 4.

In the picture on the left, it can be seen that the cutter is divided into three stages in the whole process of rock breaking. The first stage cutter just starts rock breaking, and the force gradually increased. The second stage is that the cutter starts to break the rock smoothly, and the force change is stable, while the third stage of rock breaking process ends, and the force on the cutter drops sharply. However, the normal and rolling force have three sudden decreases in the stable rock breaking stage in the right Fig. The stress of cutting cutters and particles is recorded in the PFC program, and the reason of this phenomenon can be analyzed, as shown in Fig. 5.

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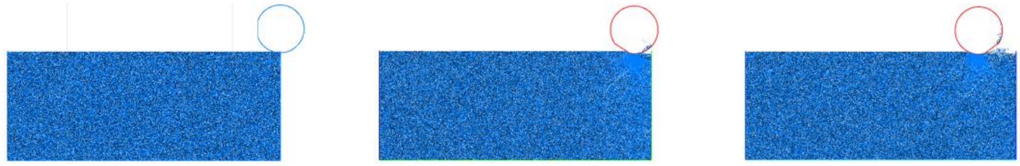
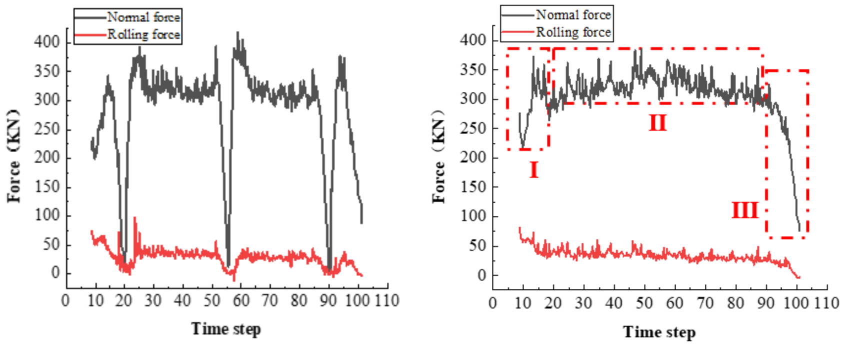


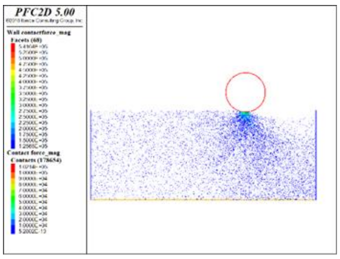
(a)the starting state *(b)the partial wear of cutter* *(c)the intact part of cutter*

Figure 3: The rolling process of partial wear 5mm cutter

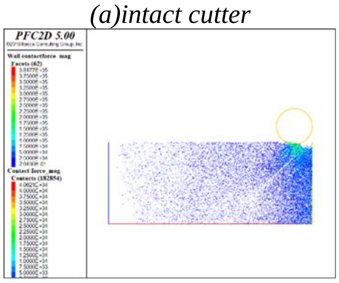


(a) *(b)*

Figure 4: The cutter force variation



(a)intact cutter



(b)partial wearing of 5mm

Figure 5: The interaction of cutter and rock

It can be seen that during the rock breaking process of the complete cutter, the fluctuation range of the cutter and contact force is not large, while during the rock breaking process of the partial wear 5mm cutter, when the cutter contacts the rock breaking at the partial wear, the force suddenly decreases, while the cutter force also decreases correspondingly under the influence of the force interaction. Therefore, the force drop of the cutter is caused by rock breaking at the cutter partial grinding. The reason may be that the penetration of the cutter partial grinding is reduced, and the contact area between the cutter and particles is reduced.

Therefore, it will have a great impact on the rock breaking force of the cutter if the rock breaking force is continued on the grinding cutter, and the influencing factors of the force change of the cutter will be specifically analyzed in the following research. From this, it can be inferred that the force change of the cutter will intensify and the cutter will be damaged abnormally probably under which conditions. The change degree of the force of the cutter is measured by the force drop index of the cutter. The larger the force mutation amplitude, the cutter is more vulnerable to impact and damage. The cutter force drop index is defined as A_1.

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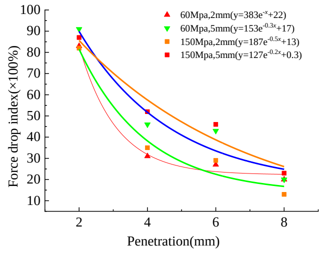
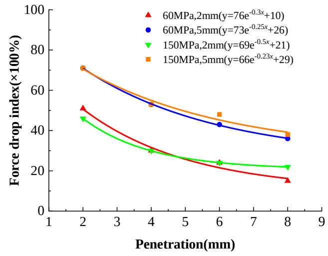
$$A_1 = \frac{\overline{F}_1 - \overline{F}_2}{\overline{F}_1} \times 100\% \tag{1}$$

Among them, $\overline{F}_1$ indicates the average force at the complete part of the cutter; $\overline{F}_2$ indicates the average force at the partial wear of the cutter.

In PFC2D program, based on the classical CSM model, two abnormal cutter models of partial wear 2mm and partial wear 5mm are respectively established for comparative tests. At the same time, each cutter is broken under two rock conditions of 60MPa and 150MPa and four penetration conditions of 2mm, 4mm, 6mm and 8mm. 16 sets of numerical simulation tests are carried out totally, and the statistics of the force drop index of cutter at the partial wearing position are shown in Fig. 6.



(a)normal force drop



(b)rolling force drop

Figure 6: The force drop index of cutter at the partial wearing position

As shown in Fig. 6, both normal force and rolling force of partial wearing cutter decrease have exponential function relation with penetration. With the increase of penetration, the decrease of normal force and rolling force of the cutter at the partial wear decreases, and the decrease speed gradually slows down. The reason may be that the force of the cutter is mainly effected by the contact between the cutter and the rock, while the penetration degree is small, the area of the cutter with the rock is least contacted, but the area difference of rock contact with the cutter is the largest, thus the force drop of the cutter is the largest. However, with the increase of penetration, the difference between the contact rock area at the partial wearing of the cutter and the complete part of the cutter decreases, so the change of the force drop of the cutter gradually slows down.

In addition, when analyzing the influence of cutter partial wear quantity on the cutter force drop, we can see that the reduction of normal force and rolling force of 5mm cutter are larger than that of 2mm cutter under the same conditions, the reason may be that when the penetration is relatively small but the partial wear is large, the cutter cannot even touch the rock, resulting in a sharp decrease in the force and an increase in the force drop index. Besides, normal force and rolling force of cutter decrease have no certain rule with the change of rock strength, so rock strength may not be the main factor affecting the force decrease of partial wearing cutter.

The specific energy of cutting cutter breaking rock has always been an important index used by many experts and scholars to measure the efficiency of cutting cutter breaking rock [16]. The specific energy formula is as follows:

$$SE = \frac{\overline{F}_n p + \overline{F}_r s}{V} \tag{2}$$

Among them, $\overline{F}_n$ represents the average normal force; p represents penetration; $\overline{F}_r$ represents

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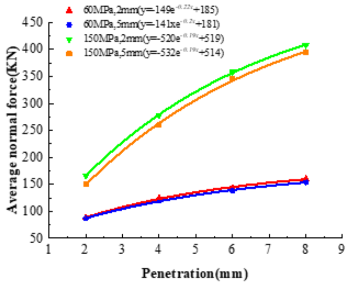
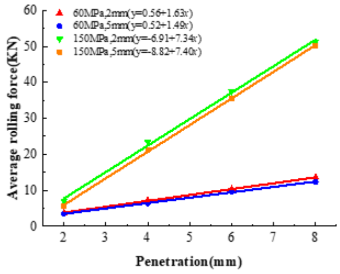
the average rolling force; S represents cutter movement distance; V represents the volume of rock breaking. The rock breaking volume of cutter can be estimated and the specific energy of rock breaking can be calculated by simulating the development of rock cracks and the contact and crushing of particles.



(a)average normal force



(b)average rolling force

Figure 7: Average cutter force

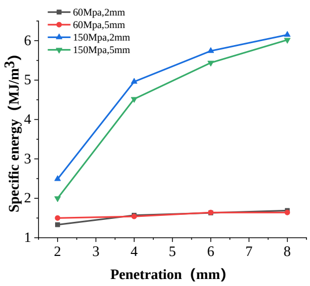


Figure 8: Specific energy varies with penetration

As shown in Fig. 7 and 8, the average normal force of partial wearing cutter has a nonlinear functional relationship with the penetration, while the average rolling force has a linear functional relationship with the penetration. Under the condition of high strength rock, the rock is difficult to be broken, resulting in a larger specific energy of rock breaking. Moreover, when other conditions are consistent, the corresponding increase of rock breaking specific energy and the decrease of rock breaking efficiency will be led to with the increase of the partial wearing extent of the cutter. Therefore, in the actual engineering project, it is necessary to find out the abnormal damage cutter and replace it in time so as to prevent the cutter from being more damaged or even bearing damage due to the abnormal cutter, which will affect the excavation efficiency seriously.

3.2 Rock breaking simulation of adjacent cutter with wear height difference

Similarly, during the excavation of TBM, due to the difference of rock properties in different parts of the tunnel face, the cutter wear at different positions on the cutter head is also different, and then the force difference between the adjacent cutter will be caused by the difference of penetration. In this paper, two cutter are used to set the wear height difference with different penetration, and the two cutter are penetrated into the rock at the same time, which can better simulate the construction mode of TBM cutter. The interaction process between rock and cutter is shown in Fig. 9.

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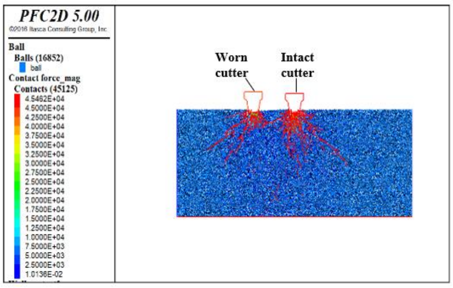
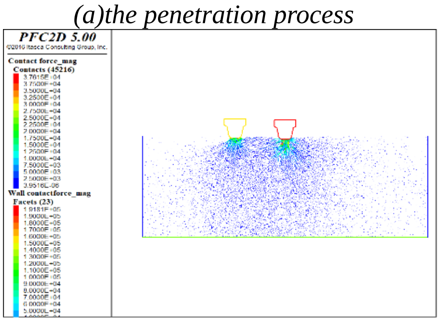


(a)the penetration process



(b)the contact force

Figure 9: The interaction between rock and 2mm height cutter

As shown in Fig. 9, the normal force of rock breaking decreases due to the small penetration of the worn cutter. Similarly, the force difference between the two cutter is defined as A_2 .

$$A_2 = \frac{\overline{F}_1 - \overline{F}_2}{\overline{F}_1} \times 100\% \tag{3}$$

Among them, $\overline{F}_n$ indicates the average normal force of the complete cutter, $\overline{F}_r$ indicates the average normal force of the worn cutter. In this paper, 18 groups of rock breaking numerical simulation tests were carried out, and the stress difference between adjacent cutter was analyzed under the conditions where 60MPa and 150MPa strength rocks are set to make wear height difference (h=1/2/3mm) cutter model in different penetration (p=4/6/8mm), and the force difference between two cutters was obtained as shown in Fig. 10.

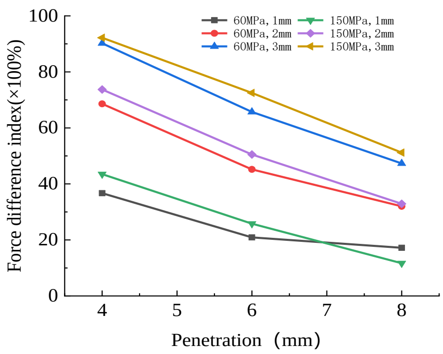


Figure 10: Force difference between two cutters

As shown in Fig. 10, the force difference between two cutters has a negative correlation with the penetration, which decreases with the increase of penetration. However, under the condition of the same consistent penetration, the difference of two cutters is affected by the difference of wear height between two cutters. The larger the difference of height, the larger the difference of force. In addition, generally speaking, the higher the rock strength, the greater the difference of the normal force between two cutters.

In addition, the criterion whether the fracture between two cutters can be extended to form rock breaking slices is also used to evaluate the rock breaking efficiency with wear height difference of cutter in the paper. Due to the limitation of space, only the formation of rock fragments under 60MPa rock with penetration of 4mm is listed, as shown in Fig. 11.

As shown in Fig. 11, when there is no height difference between adjacent cutters, the cracks between the two cutters develop and can penetrate through each other to form slices. However, as the wear height difference increases, the amount of cracks under the worn cutter decrease, and it is difficult to connect with the rock fracture of the complete cutter, and then form slices. It can be said that when the height difference is large and the penetration is low, slices between the two cutter are difficult to form, and the rock breaking efficiency will be greatly reduced. Therefore, in practical engineering projects, special attention should be paid to reducing the excessive height difference between adjacent cutters. On the one hand, cutter whose wear is large enough should be found and replaced in time. On the other hand, the abnormal condition of cutter can be detected in real time through changes in machine parameters of the TBM.

4. Conclusions

Based on the actual situation of abnormal cutter damage in the engineering site, this paper sets up two numerical simulation schemes that may cause and aggravate abnormal cutter damage, and the influence of multiple factors on the stress change and rock breaking efficiency of cutter is discussed, and the following conclusions and prospects are obtained.

If cutter has already produced partial wearing, huge differences in the force of the cutter itself will led to continuing to break the rock at this time, and greater damage will be caused when the partial wearing position of cutter hits the rock, such as blade wheel chipping, fracture, or even bearing damage, etc., and this force change will be intensified when the partial wear is large and the penetration is low. At the same time, the specific energy of rock breaking of damaged cutter will also increase and the rock breaking efficiency will decrease. Therefore, abnormal damage cutter should be found and replaced in time to avoid greater damage.

If the wear height difference occurs due to uneven wear of adjacent cutter, huge difference in the stress of two cutters will be resulted in continuing rock breaking at this time, and uneven stress of cutting cutters will be aggravated with high-strength rock mass conditions and large difference of wear height, which is easy to cause abnormal cutter damage and even serious consequences of cutter head damage. In this case, the rock fracture between the two cutters is not easy to penetrate through and form slices, which will also reduce the rock breaking efficiency. Therefore, it is necessary to check cutters in the project timely or detect the abnormal state of the cutter in real time through the change law of the machine parameters of the TBM.

In addition, relevant experiment research should be carried out in the future to confirm the conclusion of numerical simulation test, and the quantitative relationship between the force change of the cutter and the abnormal damage of the cutter should be considered, seeking to establish a prediction and early warning model for abnormal damage of cutter based on experimental data, which will have certain guiding significance for practical engineering project.

Acknowledgments

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