ROCK CUTTING MECHANICS MODEL OF TBM DISC CUTTER AND EXPERIMENTAL RESEARCH

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As one of the major boring tools of Tunnel boring machine (TBM), disc cutter was applicable in hard and medium hard rock layer. The disc cutter cutting mechanism was researched and the brittle fracture of rock based on the Mohr-Coulomb strength theory was analyzed. By establishing cutter load calculation model considering the function of dense nuclear, the expression of vertical propulsion of cutter was reached. A two-dimensional numerical simulation method which was used for simulating rock-breaking process was established based on the particle discrete element method and a rock breaking experiments conducted on the linear cutting experiment platform was carried out. The average errors between the calculation results, the simulation results and the experiment results were small, which has delivered a result to prove the effectiveness of the mechanics model. The establishment of mechanics model provided theoretical basis for studies on disc cutter cutting mechanism.

Keywords: Tunnel Boring Machine (TBM); disc cutter; mechanics model; PFC; rock breaking experiments

1. Introduction

Tunnel boring machine (TBM) is the main tool of tunneling in underground space. The disc cutter, as one of the typical cutting tools of TBM, is directly involved in the work of tunneling breaking rock in the process of construction. Well, studying the mechanism of action between disc cutter and rock to analyze loading law of disc cutter and establish mechanical model of the cutter are beneficial to the research and analysis of thrust and torque for cutter head as well as the tunneling performance of TBM. It is of great significance to improve the tunneling efficiency of shield machine. Domestic and foreign scholars have done a lot of research on the rock breaking mechanism of disc cutter. Evans has studied the rock breaking process of disc cutter. He thinks that the the rock is considered to be compressive breaking. And the magnitude of the vertical thrust required disc cutter is proportional to the projected area of rock surface in the area where the disc cutter is pressed into the rock [1]. The Japanese scholar Tosaburo Akiyama thinks that the force condition of disc cutter can be studied by two

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theoretical calculation methods: extrusion crushing theory and shear crushing theory [2]. The Japanese scholar Y. Nishimatsu thinks that the rock breaking surface belongs to the shear failure. The rock is broken and compacted to form a dense core, and the cutter cutting force expression of rock shear failure was obtained based on the molar strength theory [3]. Professor Tan Qing of Central South University used finite element software to model and analyze the triaxial force in rock cutting process of disc cutter [4]. On the basis of contact stress model, Tu Changfeng of Central South University established the lateral force prediction model of disc cutter [5]. Based on the theory of shear stress and strength, this paper analyzes the action of compacted core rock mass, establishes the model for calculating the load of disc cutter based on Moor-Coulomb strength theory considering the action of dense nuclei. Finally, we obtain the mechanical expression of the disc cutter invading rock, which provides a theoretical basis for the research of tool design.

2. Cutting Mechanism of TBM Disc cutter

The disc cutter is the main rock breaking tools of TBM in the tunnel excavation process. On the one hand, disc cutter rolling on the excavation face due to friction action of rock. On the other hand, disc cutter moving along linear invading motion under the thrust of the cutter head. When the cutter load exceeds the strength of the rock, rock fracture and detachment. The TBM diagram as shown in Fig. 1 [6-7].

Fig. 1. Tunnel boring machine (TBM)

By studying the process of disc cutter invading into rock, it can be found that a high stress zone is firstly formed in the inside of rock under the cutter’s edge, and the internal micro-crack is compacted and closed because of the action of cutter. When the stress caused by disc cutter is higher than the strength of rock, Rock breaking occurs when the stress caused by disc cutter exceeds the strength of rock. The forming process of dense core is that the rock produces small and broken particles and broken particles by the action of disc cutter, such as pulling and pressing, shearing and so on. And then it is pressed into a comminuted body, thus forming dense core. The inner energy of rock is transferred to the nearby region by the dense core, which makes the rock produce new cracks. The cracks propagate to both sides and deep of the blade in different paths, forming intermediate cracks, lateral cracks and radial cracks and so on. The lateral crack can be extended to the free surface to form block rock and flake off, while the middle crack and radial crack can cause the failure fracture in the deep part of the rock. The rock fracture system when the disc cutter invades and breaks into the rock is shown in Fig. 2 [8-10].

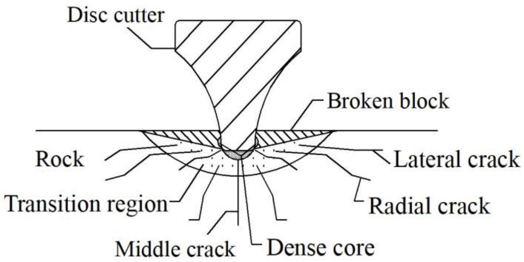


Fig. 2. Failure diagram of rock under the action of disc cutter

3. Mathematical model of invading and breaking rock with disc cutter

When invades the rock, the contact stress between disc cutter and rock produces great contact stress in the smaller volume, thus forming a dense core under and near disc cutter. The upper side of disc cutter is broken and peeled off prematurely. According to the Moorn-Coulomb failure criterion [11], the fracture of rock is assumed to be caused by shear stress and obeys the Mohr-Coulomb strength theory. The fracture surface is subjected to compression stress σ and shear stressτ as shown in Figure 3. As can be seen from Figure 3, the shape of a dense core is made up of a circular arc, with the circle center of which is O’ and radius is r as well as the length of the highest point of the arc to its bottom, i.e. the length of the dense nucleus, is a. As shown in Fig. 3 is the mechanical model of micro-element dθ of disc cutter head invading into rock, and the diagram of stress distribution in the section of disc cutter shown in Fig. 4.

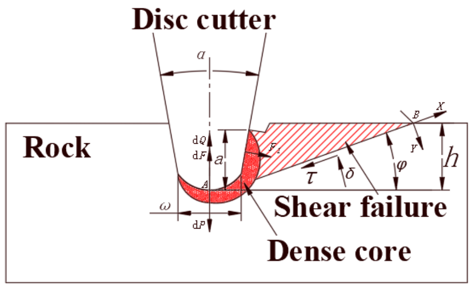


Fig. 3. The mechanical model of micro-element dθ of disc cutter head invading into rock

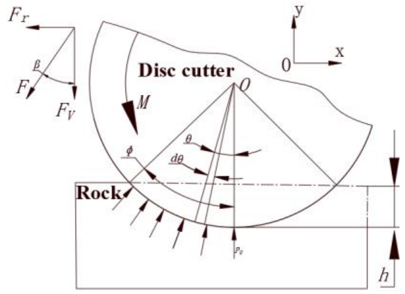


Fig. 4. The diagram of stress distribution in the section of disc cutter

If the depth of rock invasion by the head of micro-element dθ for disc cutter is h, it must overcome the strength of rock dQ and the friction df when invades a rock according to the analysis of mechanics calculation method. The force applied to micro-element dθ for disc cutter when it invades the rock is as follows:

$$dP = dQ + dF \tag{1}$$

where, the rock breaking strength dQ is the product of the projected area of the invading edge in the vertical direction and the compressive strength of the rock.

$$dQ = [2a\tan(\frac{\alpha}{2}) + w]Rd\theta\sigma_c \tag{2}$$

where, α is the blade angle of disc cutter, R is the radius of disc cutter, $d\theta$ is the angle of micro-element dθ, σ_c is the uniaxial compressive strength of the rock, a is the h is the length of dense core, and w is the width of the cutting edge.

According to the geometric relation shown in Figure 3, the resultant force of the dense core acting on the broken rock is as follows:

$$F_1 = 2\int_0^{\frac{\pi}{2}-\frac{\alpha}{2}} rRd\theta\sigma_C \cos\xi d\xi = 2aRd\theta\sigma_C \cos(\frac{\alpha}{2}) \tag{3}$$

When the force is large enough, the rock block is broken with the breaking angle 2β along the line AB under the action of shear stress, and the ultimate shear stress satisfies the Moorn-Coulomb theory.

$$\tau = c + \sigma\tan\phi_b \tag{4}$$

where, τ is the shear stress on the shear plane, σ is the normal stress on the shear plane, ϕ_b is the internal friction angle, and c is the cohesive force of the rock.

Through force balance analysis of the broken block, it can be obtained that:

$$\begin{cases} \sum X = 0 \quad F_1\sin(\frac{\pi}{2}-\frac{\alpha}{2}-\varphi) - \tau hR\sin\varphi d\theta = 0 \\ \sum Y = 0 \quad F_1\cos(\frac{\pi}{2}-\frac{\alpha}{2}-\varphi) - \sigma hR\sin\varphi d\theta = 0 \end{cases} \tag{5}$$

where, h is the depth of invasion, φ is the angle between shear plane and horizontal plane, as φ=(π-2β)/2, 2β=120°~150°[12].

The length a of dense core a can be obtained by substituting formula 3 and 4 with formula 5. The value of a is:

$$a = \frac{c\sin\phi}{2\sigma_c \cos(\frac{\alpha}{2})\left[\sin(\frac{\pi}{2}-\frac{\alpha}{2}-\phi)-\tan\varphi_b\cos(\frac{\pi}{2}-\frac{\alpha}{2}-\phi)\right]}h \tag{6}$$

In addition, the components of the wedge surface on both sides of the rock breaking strength dQ of disc cutter are balanced with the rock positive pressure dN_1, namely:

$$2a\tan(\frac{\alpha}{2})Rd\theta\sigma_c = 2dN_1\sin(\frac{\alpha}{2}) \tag{7}$$

So the total friction force of the blade invading is:

$$dF = 2\mu dN_1\cos(\frac{\alpha}{2}) = 2\mu aRd\theta\sigma_c \tag{8}$$

where, μ is the coefficient of friction between rock surface and wedge of disc cutter, with μ=0.4~0.55[13].

Therefore, the head of the microelement dθ of disc cutter invades rock and is subjected to the following forces:

$$dP = dQ + dF = [2a\tan(\frac{\alpha}{2}) + 2\mu a + w]Rd\theta\sigma_c \tag{9}$$

Through a large number of experiments and the logarithmic regression analysis and dimensional analysis of the experimental data, Rostami [14] obtains the calculated results show that the pressure distribution in the crushing region along the circumferential direction satisfies the following formula:

$$P = P_0\left(\frac{\theta}{\phi}\right)^{\psi} \tag{10}$$

where, θ is a specific position in the circumference with value between 0 and ϕ; ψ is the contact pressure distribution index with value between -0.2 and 0.2, here takes it as 0.1 [15]. P_0 is the datum stress located directly below disc cutter as dp per unit length, that is:

$$P_0 = [2a\tan(\frac{\alpha}{2}) + 2\mu a + w]\sigma_c \tag{11}$$

So the resultant force in the contact region of disc cutter is:

$$F = 2\int_0^{\phi} RPd\theta = \int_0^{\phi} RP_0\left(\frac{\theta}{\phi}\right)^{\psi} d\theta = \frac{2RP_0\phi}{1+\psi} \tag{12}$$

The lateral force on both sides of the invading rock broken by the disc cutter is equal and the direction is opposite. The rolling horizontal force is 0 and the vertical force is:

$$F_V = F\cos(\beta) = \frac{2R\phi}{1+\psi}\cos(\beta)[2a\tan(\frac{\alpha}{2}) + 2\mu a + w]\sigma_c \tag{13}$$

where, β is the angle between the resultant force of vertical force and rolling force and the vertical direction of disc cutter, with β≈ϕ/2.

4. Discrete element modeling of disc cutter invading rock

4.1 Establishment of numerical model

In the process of establishing a model by using a particle flow program, the model parameters are calibrated by uniaxial compression and Brazilian splitting numerical test. The numerical model of disc cutter of breaking rock as shown in Figure 5, with which the rock size is 300 mm × 160 mm. The disc cutter is designed according to the size of a 17 inch constant section used in the laboratory.

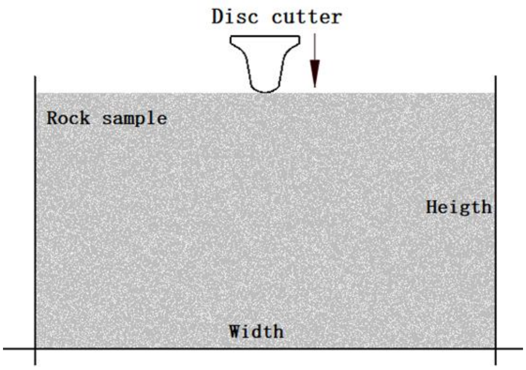


Fig. 5. The numerical model of disc cutter of breaking rock

According to the standard of rock mechanical test performance, three kinds of rock samples were made: $\phi 50mm \times 100mm$ and $\phi 50mm \times 50mm$. The mechanical properties of rock samples were obtained as shown in Table 1 after testing the mechanical parameters of rock samples.

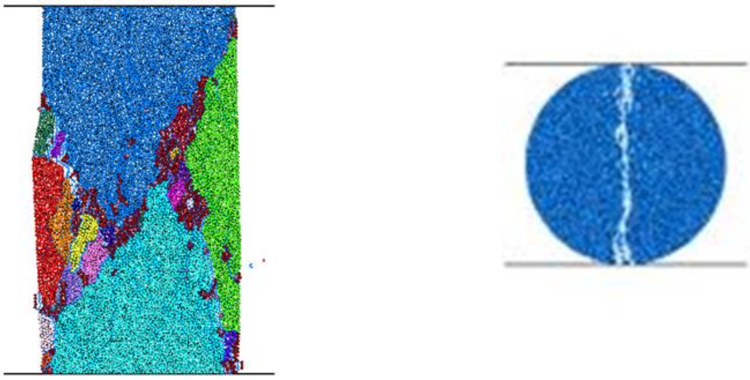
Table 1

Macroscopical parameters of hard rock materials

Density / kg·m^{-3}	Modulus of elasticity /GPa	Compression strength / MPa	Tensile strength / MPa	Poisson ratio	Cohesive force / MPa	internal friction angle /°
2516	11.45	100.33	5.69	0.25	22.7	38.45

Based on the mechanical tests of rock samples, the uniaxial compression and Brazilian splitting of rock samples in the numerical model are simulated. As shown in

Fig. 6, appropriate mesoscopic parameters are selected to match the macroscopic parameters in Table 1 after continuous calibration, and the meso-parameters of rock samples in the discrete element model of particles are shown in Table 2.



(a) Uniaxial compression (b) Brazilian splitting

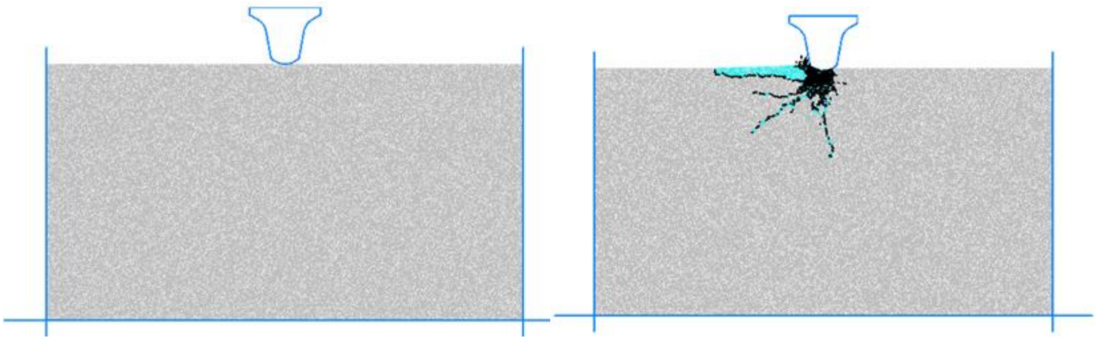
Fig. 6. Calibration of mesoscopic parameters of discrete element model

Three groups of simulated experiments were carried out for the penetration depth of disc cutter 2 mm, 6 mm and 10 mm respectively. The simulation results of disc cutter invading rocks were obtained after numerical simulation, as shown in Fig. 7. Table 3 shows the numerical simulation results.

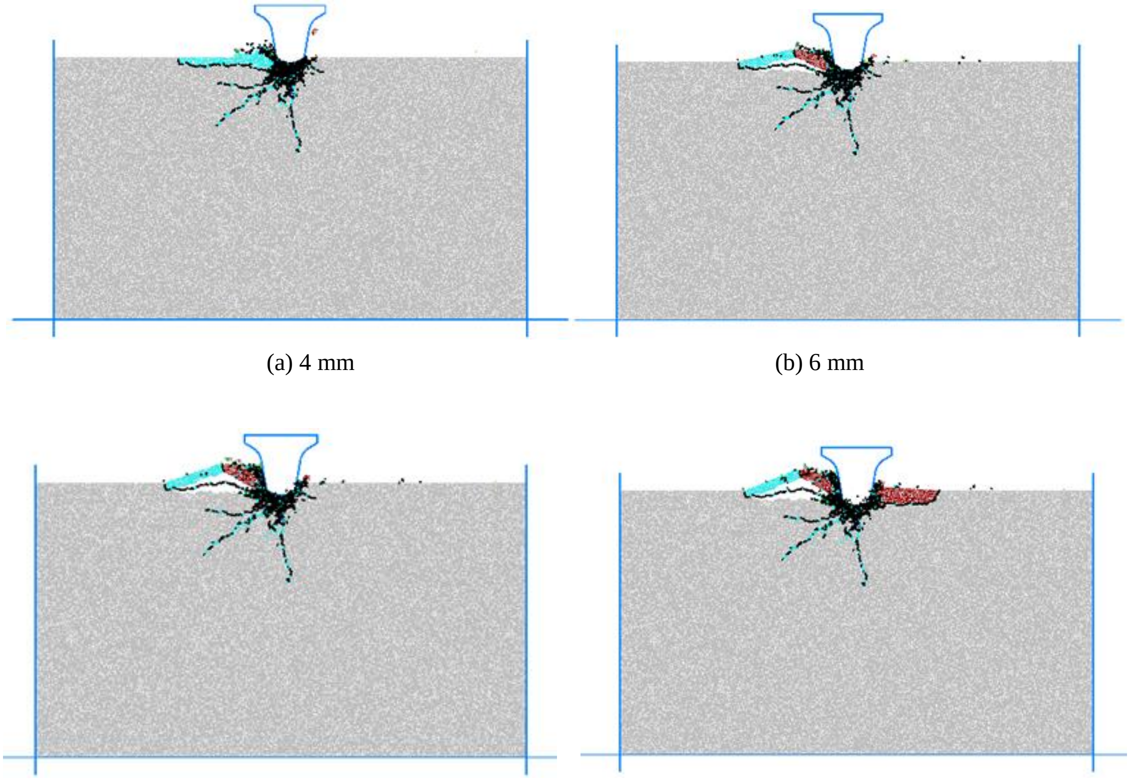
Table 2

Meso-mechanical parameters

Particle density / $kg \cdot m^{-3}$	Normal strength/ MPa	Tangential strength/ MPa	Normal stiffness/ N·m-1	Tangential stiffness/ $N \cdot m^{-1}$	friction factor
3145	86.5	86.5	1.67×10^{10}	6.67×10^{9}	0.1



(a) 0 mm (b) 2 mm



(a) 4 mm (b) 6 mm

(c) 8 mm (d) 10 mm

Fig. 7. Rock breaking of different invasive depth of disc cutter

Table 3

Numerical simulation results

Penetration depth /mm	0	2	4	6	8	10
Vertical force /kN	0	95	154	190	225	261

5. Invading experiment of disc cutter

5.1 Experimental installation

As shown in Figure 8, the invading experiment of rock of disc cutter is carried out by the straight line experiment bench, which consists of four parts: the frame, the horizontal table, the hydraulic system and the electric control test system. The whole experiment bench is driven by hydraulic system. The vertical hydraulic cylinder drives the upward and downward straight motion of the disc cutter, and the longitudinal feed of rock is driven by the longitudinal hydraulic cylinder.

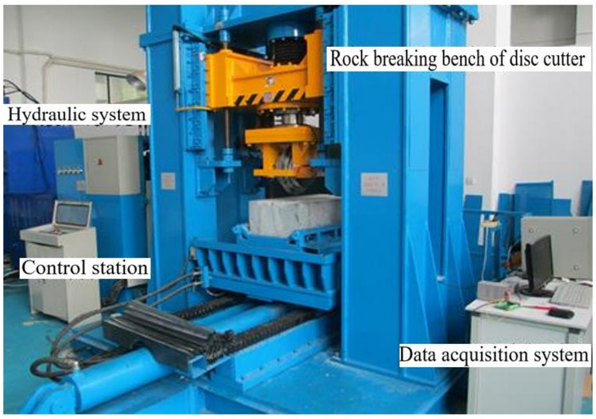


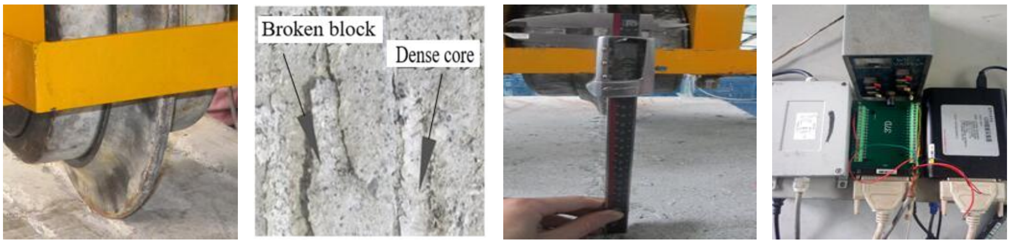
Fig. 8. Straight line rock breaking experiment bench of disc cutter

5.2 Results of experiments

In the experiment, the disc cutter and the three direction force sensor are installed on the tool holder, and the disc cutter is adjusted to directly above the experimental rock, as shown in Figure 9. The vertical force is applied to disc cutter through the loading device of vertical hydraulic cylinder. And then the experiment of rock invasion and destruction is carried out. The experimental disc cutter uses a 17-inch constant section with a diameter of 432 mm, a blade width of 18 mm and a blade angle of 20°. The rock size is 1000 mm× 500 mm × 300 /mm, and mechanical parameters are as follows: compressive strength is 100.33 MPa, tensile strength is 5.69 MPa, elastic modulus is 11.45 GPa. A Vernier caliper with a percentile is used to measure the depth of disc cutter invasion and data acquisition card is used to collect and process the data corresponding to vertical force.

Fig. 9. Installation of bench components

The vertical hydraulic oil cylinder continuously exerts pressure on disc cutter through the moving crossbeam to make the disc cutter penetrate into a certain depth, observing the situation when disc cutter invades the rock and measure depth of invading rock. It also measure the vertical force through the three-way force sensor. Fig. 10 shows the experimental process of disc cutter invading and breaking rock. According to the parameters of disc cutter and rock used in the experiment, the comparison between the calculation results of the mathematical prediction model Formula (13) and the experimental results of the vertical force corresponding to the penetration depth of disc cutter is shown in Table 4.



(a)Disc cutter invading rock; (b) Measurement of invasion depth in crater; (c) Measure the depth of invasion; (d) data acquisition

Fig. 10 Experimental Process

Table 4

Calculation results of mathematical prediction mode and Experimental results

Invasion depth /mm		0	2	4	6	8	10
Vertical force /kN	calculated value	0	98	149	176	211	236
	experimental value	0	77	138	170	205	230

6. Results comparison

The numerical simulation results are compared with the experimental results by calculating the mathematical prediction model of TBM disc cutter invading rock. The relationship between the three results is shown in Fig. 11.

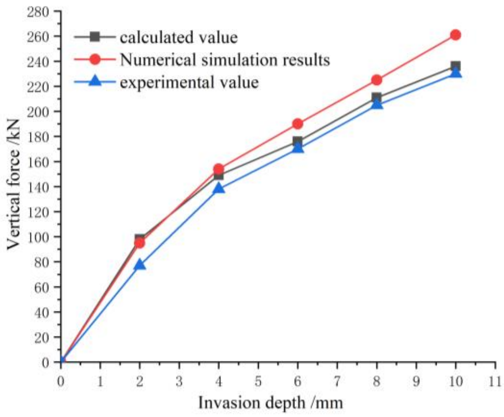


Fig. 11. Comparison of three results of invading breaking rock model with disc cutter

It can be seen from Fig. 11 that the vertical propulsion force of disc cutter invading the broken rock increases with that increase of invasion depth. Meanwhile the error between the calculated results of mathematical prediction model and experimental results decreases with the increase of invasion depth. This is because the rock surface is uneven the initial stage of disc cutter invading into the rock. When invades the experiment, the disc cutter first presses and compacts rock surface, and the microcracks inside the rock are compressed or closed. As a result of the small depth of disc cutter invasion, the vertical force measured in the experiment is small, but this factor is not considered in the mathematical prediction model. The average error between the results of the mathematical model and the numerical simulation of the invading and breaking rock of the hob is about 3.4% and that of the experimental results is about 8.3% The average error of the numerical simulation results and the experimental results is about 12.1% The results of the vertical forces calculated by the three methods are quite close. Thus, the validity and validity of the force prediction model are verified.

7. Conclusions

(a) By studying the mechanism of invading and breaking rock with disc cutter and considering the property of dense core, the mechanical prediction model of invading rock breaking with disc hob is established based on the Mohr-Coulomb theory. Finally, the expression of vertical propulsion force of invading rock breaking with hob is obtained.

(b) The particle flow model is established to simulate the invading and breaking of rock by disc cutter, and the experiment of invading hard rock by disc cutter is carried out on the straight-line experimental bench. The calculation result of mathematical prediction model of vertical force of hob invading rock is calculated. The numerical simulation results are compared with the experimental results. The error between the calculated results of the mathematical prediction model and the experimental results decreases with the increase of the invasion depth, and the average error of the three models is small, which verifies the correctness and validity of the model.

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