Numerical simulation analysis of coal rock crushed by disc cutter based on ABAQUS

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Abstract: In view of the lack of research on the mechanism of disc cutter cutting coal rock during the tunnelling process of coal mine rescue tunnel equipment, the ABAQUS software was used to establish the finite element model of single disc cutter crushing coal rock, and the influence of penetration and cutting speed on the rock breaking force during the process of disc cutter crushing coal rock was analyzed. The results show that the average cutting force increases linearly with the penetration and cutting speed. The maximum vertical force of the disc cutter at a penetration of 5mm is 2.6 times that at a penetration of 2mm. The impact of the disc cutter cutting force at a penetration of 3mm is obvious. The average rolling force at a cutting speed of 0.8 rad/s is twice that of a cutting speed of 0.2 rad/s. The impact of the disc cutter cutting force at a cutting speed of 0.5rad/s is obvious. Comprehensively considering the influence of penetration and cutting speed on the average value and fluctuation range of disc cutter cutting force, choosing a moderately large penetration and a large cutting speed parameter combination will help to achieve rapid and safe coal mine emergency rescue tunnelling. The method in this paper provides a basis for the optimization of the cutterhead tunnelling parameters during coal rock cutting.

1. Introduction

Emergency rescue in coal mine disaster accidents is an important part of mine safety work. After a coal mine collapse accident, quickly opening rescue channels is a key way to reduce personnel damage. The full face tunnel boring machine (TBM) [1] has the advantages of fast tunnelling speed, environmental protection and high comprehensive benefits [2]. The TBM cutterhead tunnelling method has become a popular research direction for quickly constructing rescue channels. Unlike stable rock formations, collapsed coal rock formations are characterized by coal rock discontinuities, and the formations are prone to secondary disasters when disturbed by cutting tools. Therefore, in collapsed coal rock formations, the rock breaking method of TBM disc cutter still faces great challenges. Reasonable control of disc cutter tunnelling parameters to achieve fast and safe tunnelling of TBM has become a key problem for TBM tunnelling technology.

In terms of the rock breaking performance of TBM tools, Liu et al. [3] used the discrete element method to study the experimental and numerical simulation methods of TBM rock crushing under high stress constraints. Zhou, Peng et al. [4] used granite samples as an example to analyze the process of rock crushing by double disc cutters. Hyun et al. [5] outlined the evaluation method of disc cutter...
life. Mohammadnejad, M et al. [6] proposed a new method of combining finite element and discrete element to simulate the process of rock crushing by mechanical cutter. Ellecosta, P et al. [7] analyzed disc cutter wear patterns and microscopic features, and proposed disc cutter selection methods for different rock types. Ebrahim Farrokh et al. [8] used the NAT method to establish an improved method for measuring the disc cutter wear rate, and researched the relationship between the disc cutter wear rate and the disc cutter spacing. Shi, Y P et al. [9] obtained the contact load distribution between the disc cutter and the rock through experiments. Lin et al. [10] studied the rock breaking characteristics and sensitivity of rock breaking parameters of the disc cutter under different rock conditions. H. Munoz et al. [11] used uniaxial compression tests to study the inherent specific energy and strain energy during the cutting process. Zhang Guiju et al. [12] used Abaqus software to perform dynamic simulation and mechanical analysis on the rock breaking process of the disc cutter. Although the disc cutter, as the main rock-breaking tool of the TBM cutterhead [13], has been the key research object of the engineering community, the theoretical research and experiments of disc cutter crushing coal rock have not been reported. Therefore, the study of the mechanism and related performance analysis of coal rock crushing by disc cutter is very important.

Based on the above reasons, this paper adopts ABAQUS to simulate the process of rock breaking by disc cutter under coal conditions, and establishes a finite element model of coal rock crushing with a single disc cutter. Influencing factors of disc cutter crushing of coal rock is analyzed, the mechanism of disc cutter crushing of coal rock is revealed, which provides a basis for the optimization of cutterhead tunnelling parameters during coal rock cutting.

2. Finite element model of disc cutter crushing coal rock

2.1. Three-dimensional numerical model of disc cutter and rock

The steps of finite element analysis of disc cutter crushing coal rock include: geometric model establishment, meshing, boundary load application, defining element and material models, defining boundary conditions, etc. Since the disc cutter is made of high-strength steel, its modulus of elasticity is much higher than that of rock, so the wear and deformation of the cutter can be ignored. The disc cutter model in this paper is a simplified model using the actual size of a 19-inch disc cutter, as shown in Figure 1.
Figure 2. The finite element model diagram.

The three-dimensional 8-node reduced integration unit (C3D8R) is used for meshing. Considering the simulation time and accuracy, the rock model only refines the grid at the disc cutter rolling position. The contact between the disc cutter and the rock is defined as the non-linear surface-to-surface contact, the outer surface of the disc cutter is the active surface, and the rock surface is the driven surface. During the loading process, the bottom of the rock is defined as fully constrained, and the speed of the disc cutter is set to 0.4 rad/s. The finite element model of disc cutter crushing coal rock is shown in Figure 2.

2.2. Material model establishment
The disc cutter material is set to be cemented carbide steel, the density $\rho$ is 7850 kg/m$^3$, the elastic modulus $E$ is 210 GPa, and the Poisson's ratio $\nu$ is 0.3. The basic parameters of coal rock are shown in Table 1.

| Density (kg/m$^3$) | Elastic modulus (MPa) | Friction angle (°) | Flow stress ratio | Yield stress (MPa) | Poisson's ratio |
|--------------------|-----------------------|-------------------|------------------|--------------------|-----------------|
| 1500               | 1400                  | 30.2              | 0.778            | 20.49              | 0.3             |

According to the way the TBM cutterhead works in the mine and based on the structural characteristics and mechanical properties of coal rock, an extended linear Drucker-Prager plastic constitutive model [14] is established to simulate the stress-strain relationship of the geomaterials after yielding. The linear Drucker-Prager model is shown in Figure 3. The yield function and plastic potential surface function are, respectively:

$$F = t - ptan\beta - d = 0$$
$$G = t - ptan\phi$$

where:

$$t = \frac{q}{2} \left[ 1 + \frac{1}{k} \left( 1 - \frac{1}{k} \right) \frac{r^3}{q} \right]$$

In the above equation, $t$ is the partial stress, $p$ is the equivalent compressive stress, and $\beta$ is the inclination of the yield surface in the main space of $p$-$t$ stress. $\psi$ is the dilatancy angle, $q$ is the Mises equivalent stress, and $r$ is the third invariant of partial stress. $k$ is the ratio of triaxial tensile strength to triaxial compressive strength. $d$ is the intercept of the yield surface on the $t$ axis of the stress space, which is related to the input hardening parameters. There are three cases as follows:

When the uniaxial compressive strength $\sigma_c$ is used to define hardening:
\[ d = \left( 1 - \frac{1}{3} \tan \beta \right) \sigma_t \] (4)

When the uniaxial tensile strength \( \sigma_t \) is used to define hardening:

\[ d = \left( \frac{1}{k} + \frac{1}{3} \tan \beta \right) \sigma_t \] (5)

When the shear strength \( \tau \) is used to define hardening:

\[ d = \frac{\sqrt{3}}{2} \tau \left( 1 + \frac{1}{k} \right) \] (6)

Figure 3. The shape of the linear Drucker-Prager model on the \( \pi \) plane.

The crushing process of coal rock is the process of energy accumulation, so the plastic damage and destruction model is introduced (Figure 4). In the figure, \( D \) is the damage variable and \( \sigma_{yo} \) is the stress at the time of initial damage of the rock damage. \( \varepsilon_0^{pl} \) is the equivalent plastic strain corresponding to \( \sigma_{yo} \), and \( \varepsilon_f^{pl} \) is the equivalent plastic strain corresponding to the complete failure of the rock.

Figure 4. Rock damage and failure model.
3. Simulation results and analysis

The rock crushing process of the disc cutter is divided into two stages. Stage of disc cutter penetrating into rock body: disc cutter penetrates into rock body due to the radial thrust. Small pieces of crushed body are formed under the blade. The crushed body is crushed and then compacted to form a dense core. Rock fragment formation stage: the pressure of the disc cutter is transferred from the dense core to the surrounding rock, and the surrounding rock generates cracks. The cracks continue to expand, and the cracks of adjacent disc cutters penetrating into the rock body penetrate each other, forming large pieces of rock fragments and falling off. The complete rock breaking process of the disc cutter is shown in Figure 5.

The ABAQUS software was used to simulate the above process. Figure 6 shows the distribution of principal stress of rock during the dynamic rock breaking process of the disc cutter when the penetration is 4mm.

![Figure 5. Rock breaking process of the disc cutter.](image)

![Figure 6. Distribution of principal stress of rock.](image)
It can be seen from Figure 6 that there is a clear stress concentration area under the disc cutter, and the stress cloud in this area is constantly changing. The maximum stress value in the stress concentration area is 20.73Mpa, which is greater than the compressive strength of the rock. The rock breaks under the influence of compressive stress and continuously transfers the force to nearby rocks.

The cutting force of the disc cutter is mainly affected by two factors, penetration and cutting speed. According to the actual situation of TBM tunnelling, the penetration value range is set to 2-5mm, and the cutting speed value range is set to 0.2rad/s-0.8rad/s. A simulation scheme as shown in Table 2 is established. The average cutting force and maximum cutting force obtained by each group of simulation are also shown in Table 2.

### Table 2. Simulation scheme and results.

| Number | Penetration (mm) | Cutting speed (rad/s) | Mean lateral force (kN) | Mean rolling force (kN) | Mean vertical force (kN) | Maximum lateral force (kN) | Maximum rolling force (kN) | Maximum vertical force (kN) |
|--------|------------------|-----------------------|-------------------------|-------------------------|--------------------------|----------------------------|----------------------------|----------------------------|
| 1      | 2                | 0.4                   | 0.21                    | 2.1                     | 16.3                     | 2.4                        | 7.7                        | 58.5                      |
| 2      | 3                | 0.4                   | 0.37                    | 3.0                     | 30.9                     | 4.3                        | 9.1                        | 133.6                     |
| 3      | 4                | 0.4                   | 0.53                    | 3.9                     | 40.9                     | 5.0                        | 13.2                       | 149.0                     |
| 4      | 5                | 0.4                   | 0.77                    | 4.2                     | 50.8                     | 6.3                        | 12.4                       | 153.2                     |
| 5      | 4                | 0.2                   | 0.43                    | 3.8                     | 38.8                     | 4.7                        | 12.0                       | 145.8                     |
| 6      | 4                | 0.6                   | 0.81                    | 4.6                     | 45.1                     | 8.7                        | 14.7                       | 166.1                     |
| 7      | 4                | 0.8                   | 0.89                    | 4.9                     | 48.2                     | 9.1                        | 18.0                       | 178.4                     |

3.1. Influence of penetration on the cutting force of disc cutter

The variation of the mean vertical force of the disc cutter with the penetration is shown in Figure 7. The average vertical force of the disc cutter increases approximately linearly with increasing penetration. When the penetration increased from 2mm to 5mm, the average vertical force increased from 16.3kN to 50.8kN, a three-fold increase. When the penetration is small, the broken coal rock is mainly debris, and as the penetration of the disc cutter increases, large pieces of chips are gradually generated, which results in a very large difference in cutting force at different penetrations. Xue Yadong [15] designed a disc cutter rock breaking vibration test system, and obtained the relationship between the rock breaking parameters and the vibration pattern. It was shown that penetration has a greater influence on the transmission of vibration waves. The larger penetration, the stronger the vibration wave transmitted by the disc cutter. Under collapsed conditions, the stronger the vibration, the more likely the tunnel will collapse again. Therefore, in the actual shield tunnelling construction, the appropriate penetration should be selected to avoid collapse again. At the same time the efficiency
of tunnelling should be improved to ensure the rapid and safe construction of emergency rescue channels.

![Figure 7. Variation curve of cutting force with penetration.](image)

**3.2. Influence of cutting speed on cutting force of disc cutter**

The variation of the mean vertical force of the disc cutter with the cutting speed is shown in Figure 8. The mean vertical force of the disc cutter increases approximately linearly with increasing cutting speed. When the cutting speed is increased from 0.2 rad/s to 0.8 rad/s, the mean vertical force increased from 38.8kN to 48.8kN, an increase of 25%. The rapid increase of cutting force will lead to the increase of the maximum vertical force and the increase of impact, which will affect the tunnelling efficiency. At the same time, under the collapsed working conditions, the rapid increase of cutting force may cause the tunnel to collapse again, affecting life rescue work, and is not conducive to the rapid and safe construction of rescue channels. Based on the above analysis, under the premise of ensuring work efficiency and safety, the excessive cutting speed cannot be selected.

![Figure 8. Variation curve of cutting force with cutting speed.](image)

**3.3. Influence of the impact of disc cutter cutting force**

Taking the force of the disc cutter when the penetration is 4mm as an example, this paper researches the impact of the force of the disc cutter. Figure 9 is the time course of vertical force, lateral force and rolling force during the disc cutter cutting process when the penetration is 4mm.
Figure 9. Diagram of the force on the disc cutter when the penetration is 4mm.

It can be seen from the figure that during the cutting of the rock by the cutter, the forces on the disc cutter fluctuate up and down around certain values. This is consistent with the actual force of the disc cutter rock breaking during the actual tunnelling process, which is also the basic characteristic of the brittle material cutting force. The impact of the cutting force of the disc cutter is mainly manifested as the fluctuation of the vertical force. The maximum vertical force is 149.0kN, which is
3.6 times the mean vertical force. The increased impact of the cutting force of the disc cutter adversely affects the efficiency and safety of tunnelling. According to Table 2, the impact of the cutting force of the disc cutter is obvious when the penetration is 2mm to 3mm. Also, when the cutting speed is 0.4rad/s to 0.5rad/s, the impact of the cutting force of the disc cutter is obvious. Therefore, these values should be avoided as much as possible when selecting tunnelling parameters. After the tunnel collapses, the geometric dimensions of the working objects during the TBM tunnelling process are complex. When the working surface is subjected to a large impact load, it is likely to collapse again. Therefore, the penetration and cutting speed should be determined according to the impact load situation during TBM tunnelling, so as to improve the tunnelling efficiency and ensure that the rescue work of the collapse can be carried out safely and quickly.

4. Conclusion
In this paper, the numerical simulation of disc cutter crushing coal rock was carried out, which provided a new idea for studying the mechanism of TBM crushing coal rock. Based on the Drucker-Prager plastic criterion, a finite element simulation model of rock crushing by a single disc cutter was established, and the influencing factors of disc cutter crushing coal rock were analyzed. The simulation results showed that the three-way force of the disc cutter increases approximately linearly with the increase of penetration and cutting speed. The average vertical force at a penetration of 5 mm is 3.1 times that at a penetration of 2 mm. When the cutting speed changed from 0.2 rad/s to 0.8 rad/s, the average vertical force increased by 25%. Increasing the penetration can effectively improve the tunnelling efficiency, but the impact of the cutting force of the disc cutter was also significantly increased, which increased the risk of coal rock tunnelling surface collapse. Considering comprehensively the influence of penetration and cutting speed on the cutting force of the disc cutter, choosing a parameter combination with moderate penetration and a large cutting speed is conducive to achieving rapid and safe coal mine emergency rescue tunnelling.

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