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Numerical Simulation of Rock Breaking Factors with TBM Disc Cutter

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Abstract: The rock breaking effect of TBM is affected by many factors, which can be roughly divided into mechanical factors and engineering environment factors. The mechanical factors include hob ring edge Angle, ring width, single and double edge Angle, etc. Engineering environmental factors include rock strength, rock joint properties, confining pressure and so on. By using ABAQUS finite element software, under the condition of certain disc cutter angle and blade width, the influence of rock strength, joint and confining pressure on TBM rock breaking effect in engineering environmental factors is studied by analyzing the crack propagation and rock breaking force of disc cutter rock breaking process. The influence of disc cutter rock breaking on TBM rock breaking effect is analyzed in depth, which provides a basis for TBM operation prediction. Thus, the excavation efficiency and rock breaking speed of TBM can be improved.

Keywords: TBM, confining stress, excavation efficiency, rock breaking force, crack propagation.

1. Introduction

Full section tunnel boring machine (TBM) is the main tool of underground space excavation, because of its safety, high efficiency and low pollution Many advantages such as dye property are widely used in tunnel excavation. TBM promotes rock destruction through the interaction between hob and palm surface, and the quality of rock breaking effect of hob directly affects the efficiency and reliability of TBM excavation. **Gertsch**[1] studied the characteristics of linear rock cutting with hobs, and analyzed the change law of cutting depth and cutter spacing on the three-way force of hobs. **Cho**[2] used the linear cutting test bench to carry out rock breaking experiments of hob cutting different rocks, obtained the optimal knife spacing of different rocks, and used the finite element method to conduct numerical simulation, which was very close to the experimental results. **Bejari H** [3] used UDEC software to study the influence of joint spacing and joint Angle on single tool rock breaking, and the study showed that the increase of joint spacing would reduce the cutting rate of the tool, and the joint Angle between 25° and 30° was the most beneficial to the tool rock breaking. **Ghazvinian A** et al. show that the rock strength increases with the increase of confining pressure, and the rock strength first increases and then decreases with the increase of joint inclination Angle, among which the rock strength is the least when the joint inclination is 45°. These research results have great reference value for the study of disk hob rock breaking under different confining pressure and joint characteristics. On this basis, this paper uses ABAQUS finite element software to numerically simulate disk hob rock breaking under different confining pressure and joint characteristics, and studies the influence of confining pressure and joint characteristics on disk hob rock breaking, providing reference for the application of numerical simulation technology in tool rock breaking research.

2. Numerical Simulation

2.1. The process of numerical model established

The rock formations encountered by TBM excavation are generally complex and diverse, among which hard rock is the main one. The rock object simulated in this paper is common granite, whose macro-mechanical parameters are shown in Table 1.

Table 1. Rock sample model parameters

Density(ρ,kg/m3)	Young's modulus(E,GPa)	Uniaxial compressive strength (UCS,MPa)	Brailian tensile strength (MPa)	Poisson's ratio(υ)
2700	40	100	15	0.18

The rock-breaking process of real disc cutter is a three-dimensional rolling rock-breaking process. The literature [4-6] simplifies it to a two-dimensional disc cutter intrusion rock-breaking process. The research shows that the method is reasonable and feasible. On the basis of the above, the numerical model of rock breaking under different confining pressures is established as shown in figure 1.The corresponding rock sample size in the model is 400mm×160mm; According to the confining pressure value that may occur in the real excavation formation of TBM, the confining pressure on both sides of the rock is set to be 1, 5, 10, 15, 20 and 25MPa respectively. The application of constant confining pressure is shown by the arrow in Fig. 1. The boundary at the bottom of the rock is fixed and the penetration depth is set to be 10mm.

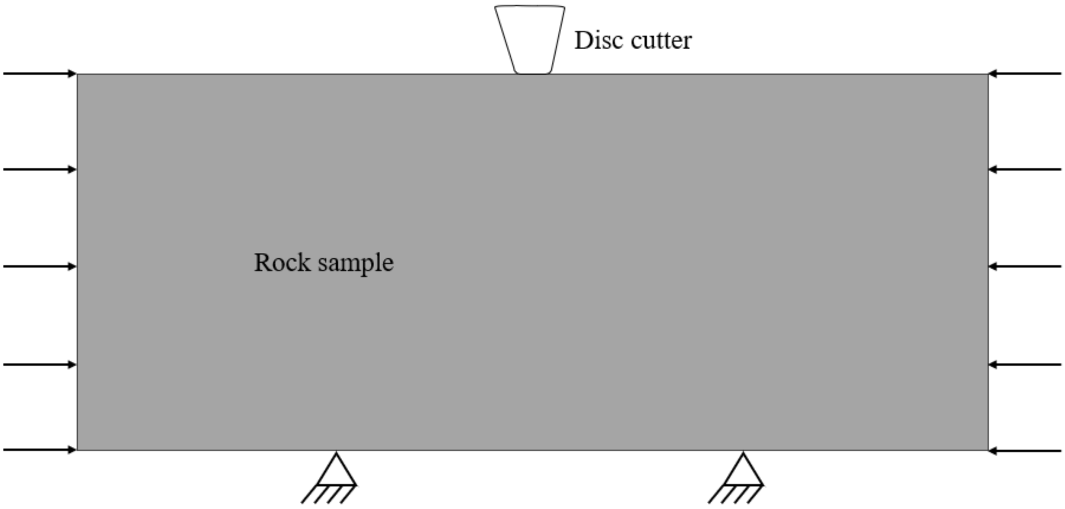

Figure 1. Disc cutter rock breaking simulation model

2.2. Analysis of rock mass breaking process

The rock breaking state of hob under different confining pressures is shown in Fig. 2. It can be seen from the figure that under the same tool width, when the confining pressure value is small, the crack propagation tends to be inside the rock mass, which is manifested as the macroscopic crack along the vertical direction and the crack length is longer. With the increase of confining pressure, the crack propagation along the vertical direction is slowly suppressed, and the crack propagation along the horizontal direction and free plane is promoted. When the confining pressure continues to increase to a large value, the propagation of cracks along the horizontal direction is also inhibited. As shown in Fig. 2(a) and (b), when the confining pressure is 1 and 5MPa respectively, the confining pressure is relatively small, and the cracks almost penetrate to the bottom of the rock mass in the vertical direction, while the propagation is relatively small in the horizontal direction. When the confining pressure is increased to 10MPa, as shown in Fig. 2(c), the crack propagation in the vertical direction under the action of hob is obviously inhibited, and the crack propagation almost turns to the horizontal direction and the free plane. When the confining pressure increased to 25MPa, as shown in Fig. 2(f), the propagation of cracks in both vertical and horizontal directions was almost suppressed, and the cracks were only confined to the vicinity of the hob blade, without obvious macroscopic long cracks.

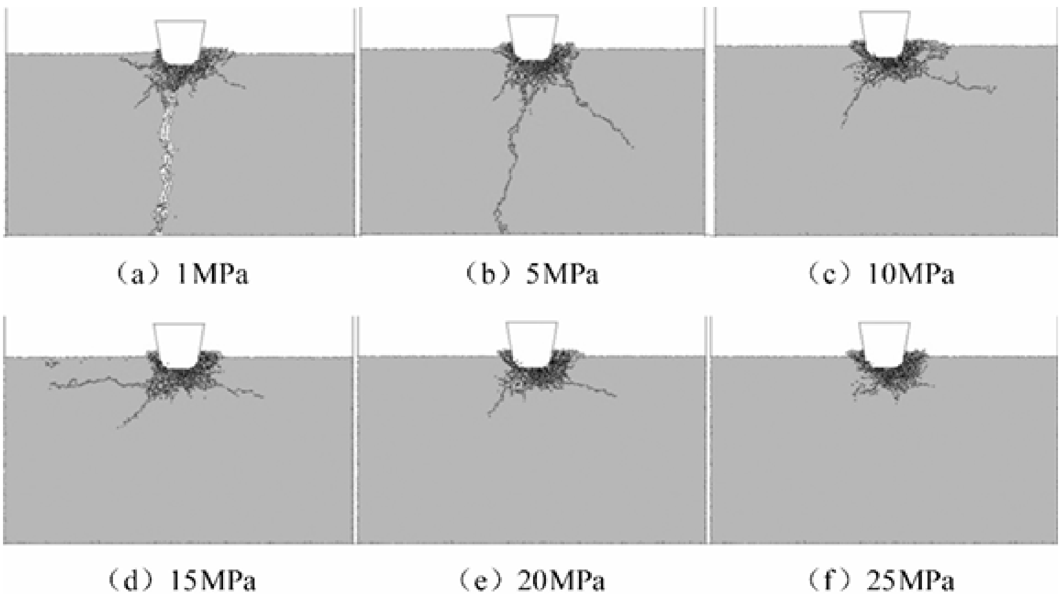

Figure 2. Rock breaking state of hob under different confining pressure

Fig. 3and Fig 4 shows the curves of the change of hob normal force and rolling force over time at different confining pressure conditions. As can be seen from Fig. 3and Fig 4, in the normal force curve, the rising stage of the curve indicates that the hob penetrates into the rock mass, and the hob force continues to rise with the increase of penetration depth. Meanwhile, fragmentation zones, micro-cracks and macro-cracks gradually form inside the rock sample and tend to be connected. By analyzing the hob force curve, the average and peak values of normal force and rolling force under different confining pressure and penetration degree can be obtained, and the results can provide a basis for the design of mechanical dynamic system parameters, construction optimization and rock mass roadability evaluation. Fig. 3 and Fig. 4 show the curves of mean normal force and mean roll force with confining pressure. When the cutter head speed is constant, the driving rate at each turn of the cutter head in the field driving process can be equivalent to the penetration index in the rock breaking test. Therefore, the influence of confining pressure on the driving rate in actual engineering can be predicted by the change law of penetration degree under different confining pressure conditions in this test.

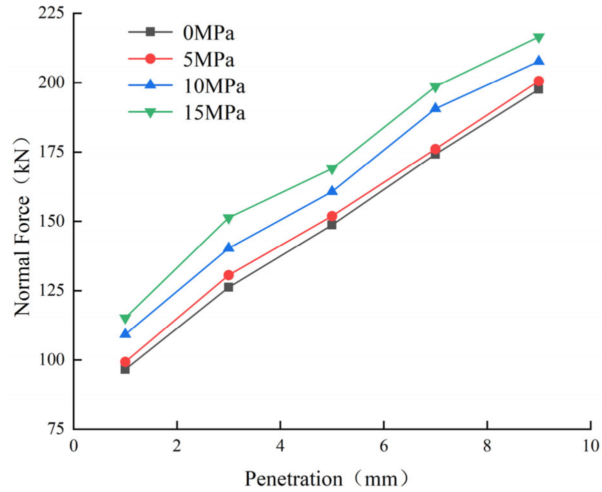

Figure 3. Penetration and average normal force curves under different confining pressure conditions

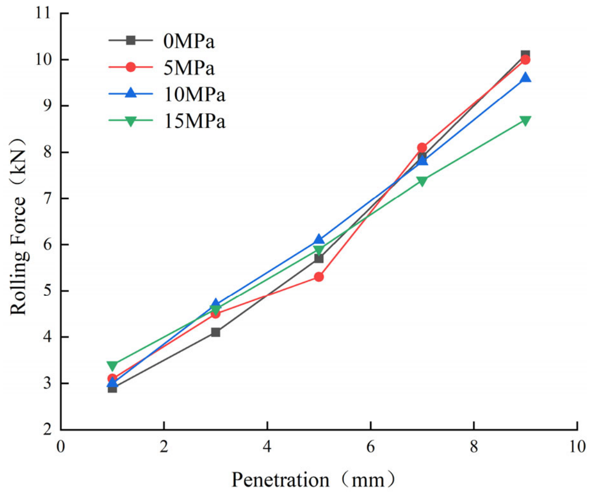

Figure 4. Penetration and average rolling force curves under different confining pressure conditions

As can be seen from Fig. 3, with the increase of confining pressure, the average normal force increases with the same penetration degree. This is because the increase of confining pressure improves the resistance strength of rock mass to hob intrusion at the same depth, limits the initiation of cracks in rock, increases the difficulty of rock breaking, and increases the normal force of hob. As can be seen from Fig. 4, under different confining pressure conditions, the average rolling force increases with the increase of penetration degree, and the average rolling force increases with the increase of confining pressure, but the increasing trend slows down significantly with the deepening of penetration degree. This is because when the cutting speed is constant (that is, the cutter head rotation rate is constant), with the increase of confining pressure, the substantial increase of normal force in the process of hob intrusion into rock mass leads to the increase of rock mass in the state of hydrostatic pressure adjacent to the hob, thus increasing the range of crushing zone and the degree of crushing.

3. Analysis of Rock Breaking Efficiency of Hob

The rock-breaking efficiency of the hob is generally characterized by the rock-breaking specific energy consumption SE. The specific energy consumption refers to the energy consumed by the crushing of the rock per unit volume. The greater the specific energy consumption, the lower the rock-breaking efficiency. Equation (1) represents the calculation formula of specific energy consumption SE:

$$SE = \frac{W}{V} = \frac{FL}{V} \tag{1}$$

where SE is the specific energy consumption of rock breaking, W is the energy consumed by the hob to break rock, F is the rolling force, L is the length of each cutting, V is the volume of rock fragments.

Specific energy SE is the work required to break a unit volume of rock mass. Generally, this index is used to evaluate the rock breaking efficiency of TBM hob under specific conditions. Fig.5 shows the trend diagram of specific energy variation with the increase of penetration under different confining pressure conditions. As can be seen from Fig.5, under different confining pressures, the variation trend between specific energy and penetration degree is similar, that is, with the increase of penetration degree, due to the increase of the proportion of large pieces of rock, specific energy will gradually decrease, and rock breaking efficiency will gradually increase, until the critical penetration degree is reached, when the specific energy value is the lowest and rock breaking efficiency is the highest. When the critical penetration degree is exceeded, the proportion of large pieces of rock increases, resulting in excessive fragmentation of rock debris, the increase of silty granular rock slag, the trend of specific energy increase, and the rock breaking efficiency decreases.

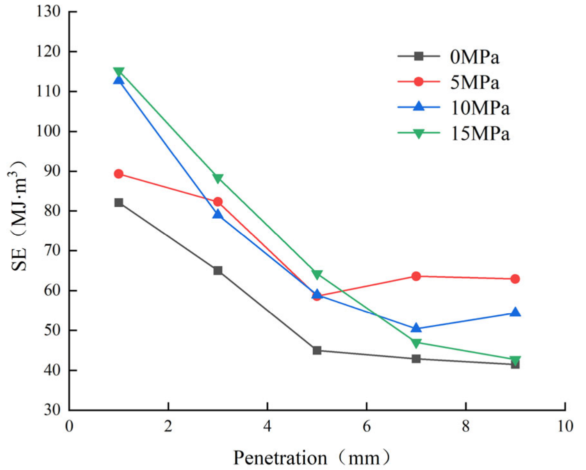

Figure 5. Penetration and specific energy consumption curves under different confining pressure conditions

4. Conclusions

By using ABAQUS finite element software, the rock breaking effect of hob under different confining pressure and penetration degree during rock breaking was numerically simulated, and the influence of confining pressure and penetration degree on rock breaking force and specific energy consumption of hob was analyzed. The main conclusions were as follows:

(1) Under the same penetration degree, with the increase of confining pressure, the limiting effect of rock sample on hob intrusion is enhanced, and the average normal force of hob increases. When the penetration degree is increased, the trend of increasing with the increase of confining pressure is more obvious. At the same time, due to the substantial increase of normal force, the crushing degree and range of the crushing zone under the hob are increased, which is conducive to the forward cutting of the hob. Therefore, when the penetration reaches the critical value, the average rolling force shows a decreasing trend, and the greater the confining pressure, the more obvious the decreasing trend.

(2) The existence of a critical penetration degree results in the lowest specific energy value and the highest rock breaking efficiency. On the whole, with the increase of confining pressure, the ratio of optimal cutter spacing to penetration decreases.

(3) When the confining pressure is small, the crack propagation is more likely to spread along the vertical direction inside the rock. With the increase of the confining pressure, the crack propagation in the rock mass gradually expands from the vertical direction to the horizontal direction and the free plane.

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