Numerical simulation of rock fracture with TBM cutter

Hangyun Zhu\textsuperscript{1*}, Lingbo Feng\textsuperscript{1}

\textsuperscript{1}School of mechanical engineering, Tianjin University, Tianjin, 300072, China

*Corresponding author’s e-mail: 15621466929@163.com

Abstract. In order to study the process of rock fracture with TBM, the three-dimensional discrete element model of hard rock with joints is established based on the discrete element method. Uniaxial compression test and Brazilian disk splitting test were used to calibrate the relevant parameters. The joints have different strength, spacing and inclination. The dynamic cutting simulation of single cutter is completed. The fracture characteristics of the jointed rock and the load on the tool are obtained. The results show that the joint characteristics have a great influence on the rock breaking properties of the cutter. When the thickness of the joint is unchanged, the rock breaking load of the cutter increases with the increase of the joint strength. When the strength of the joint is unchanged, the rock breaking load of the cutter increases with the increase of the thickness of the joint in a certain range. Moreover, under the conditions of different strength, different spacing and different inclination, the fracture characteristics of rocks are also different.

1. Introduction
In recent years, with the comprehensive development of China's south-to-north water diversion project, west-to-east gas transmission project and western development project, large-scale construction of hydropower tunnels, urban underground projects, underground tunnels, highway tunnels and other important projects has become imperative. The geological conditions in the TBM construction area are complex, with high in-situ stress, high confining pressure, joint strata and other conditions. All these conditions will affect the rock-breaking efficiency, rock-breaking load and rock-breaking reliability of TBM. Therefore, it is very important to study the rock joint.

At present, scholars have studied the rock breaking process of jointed rocks from theoretical derivation, experimental study and numerical simulation. Jalali and Zare\textsuperscript{1} designed a rotary cutting device with a group of knives and carried out multiple sets of driving experiments on gypsum blocks to analyze the impact of additional impact load on the cutter plate load. Literature\textsuperscript{2} studies the rock breaking mechanism of the rock breaking process and the rock breaking load of the cutter through the experiment of single cutter penetration into the joint rock. Entacher\textsuperscript{3} developed an experimental test device for rock breaking load of single cutter and obtained the threedirectional load in the process of tool rock breaking, studied the relevant characteristics of its load curve. With the improvement of computer hardware function and the acceleration of calculation speed, in the aspect of numerical simulation, scholars use finite element method (FEM), discrete element method (DEM), finite difference method (FDM) and other numerical methods to study such problems. In order to avoid the large deformation of the grid in the calculation which leads to the non-convergence of the calculation, the paper\textsuperscript{4} applies the finite element method based on rangelanger-euler to simulate the process of the shield machine cutting the soil, which can effectively solve the numerical divergence in the simulation process at the cost of a long time. In the literature\textsuperscript{5}, our research group developed a
set of program for parametric modeling based on ANSYS, which greatly improved the efficiency of TBM modeling, and the model is very conducive to the subsequent grid division. TBM equipment is shown in figure 1.

![TBM equipment](image)

Figure 1. TBM equipment.

2. Numerical model
Granite is used for cutting rock materials. This kind of rock belongs to the hard rock with large load on TBM cutter in tunnel construction. It is of great significance to study the process of rock breaking of this kind of rock. Specific parameters are shown in table 1[5].

| Property                  | Value |
|---------------------------|-------|
| Density                   | 2.8 t/m³ |
| Compressive Strength(MPa)| 120   |
| Tensile Strength(MPa)     | 15    |
| young's modulus (GPa)     | 11.5  |
| Poisson ratio             | 0.25  |

2.1 Selection of contact model
Contact model is an important foundation of discrete element method, which determines the force and torque between particles. EDEM software provides many contact models for different situations. Hertz-mindlin with bonding considers the bonding force between particles on the basis of the basic contact model. The particles bond with each other by connecting key. The bond can bear and transfer the force and moment between particles. When the bond is stressed to the limit force or moment it can bear, it will break, which is manifested as the fracture failure of macroscopic materials. When the bond is broken, the contact force is calculated according to the basic contact model.

2.2 Calibration and selection of rock mesoscopic parameters
The most important thing in building a model is to select the particle mesoscopic parameters that can reflect the macroscopic mechanical properties of real rock materials. Generally, the mesoscopic parameters of discrete elements are not directly related to the macroscopic physical and mechanical parameters of rock materials. Since the movement mode of particles after material destruction is determined by the basic contact model, the friction coefficient in the basic contact model is calibrated by using virtual repose angle experiment. As shown in figure 2, the virtual uniaxial compression experiment and the Brazilian disk splitting experiment are used to repeatedly select and calibrate the contact model parameters of bonding contact model. The main principle is that the elastic modulus and poisson’s ratio of macroscopic materials are mainly affected by the stiffness and stiffness ratio of contact model parameters. The tensile strength and compressive strength of macroscopic materials are mainly related to the normal and tangential limit stress of the connection bond in the contact model parameters.
Through the above method of parameter calibration, a three-dimensional discrete element model with different joint plane strength and joint spacing was established as shown in figure 3. The strength of joint surface is divided into three grades: weak, medium and high strength, and the joint surface spacing is set as 40mm, 80mm and 120mm respectively. The inclination of the joint plane is set to 60 degrees[6].

2.3 Setting of boundary conditions
The penetration degree of cutter disc in the course of hard rock driving is set as 8mm, the rotation speed of cutter disc is set as 1.1rad/s, and the mounting radius of cutter is set as 2m[7]. After conversion, the translation speed of cutter is 1.8m/s. According to the research on the sliding amount of the cutter, the rotation speed of the cutter is set to 17bpm. These parameters are in line with the actual situation, so all simulations in this paper are based on this boundary condition. The cutter cutting model is shown in figure 4.
3. Results and Discussion

3.1 Rock fracture morphology
Because joints have the effect of preventing the propagation of cracks and forces, the fracture mode of jointed rock is different from that of intact rock. Different joint features have different fracture modes. When the joint spacing is fixed, the strength of the joint surface will affect the rock fracture mode. When rock strength is low, cracks can spread to the joint surface and cause a large area of damage to the joint surface. This phenomenon is gradually disappearing with the increase of joint surface strength.

The fracture characteristics of the rock are shown in figure 5.

Figure 5. The fracture pattern of rock.
When the strength of joint surface is fixed, the spacing of joint surface will also affect the fracture mode of rock. When the joint surface spacing is relatively small, the cracks can easily propagate to the joint surface and the joint has a great influence on the rock breaking mode. When the gap between
the joint planes is greater than 120mm, the cracks will not propagate to the joint planes, which is equivalent to complete rock fracture. The fracture characteristics of the rock are shown in figure 6.

![Figure 6. The fracture pattern of rock.](image)

3.2 Cutter load analysis

Because joints have the effect of preventing the propagation of cracks and forces, joint characteristics will affect the cutter load.

When the joint spacing is fixed, the strength of the joint surface will affect the cutter load. With the increase of joint strength, the tangential force and normal force of cutter will increase. When the strength of joint surface reaches a certain level, the load will not increase. The cutter load curves are shown in figure 7.

![Figure 7. Cutter load curves.](image)

When the strength of joint surface is fixed, the spacing of joint surface will also affect the cutter load. In a certain range, the tool load increases with the increase of joint spacing. When the joint spacing reaches 120mm, the tool load will become stable. It can be seen that the existence of joints can prevent the propagation of forces and proper joints can increase the rock's breakability. The cutter load curves are shown in figure 8.
4. Conclusion
The whole process of TBM fracture jointed rock was modeled by three dimensional discrete elements method. The influence of joint on the process of TBM rock breaking is summarized. The influence of joint surface strength and joint surface spacing on rock fracture morphology and tool load is summarized and the specific range is given. The results are useful for the optimization design of TBM cutter and the adjustment of operating parameters.

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