Study on Fracture Mechanism of Soft Rock with Different Prefabricated Fractures during Drilling

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Abstract. The primary fractures in rocks have an important influence on the rock breaking efficiency. In order to understand the fracture mechanism of broken soft rock strata more deeply, this paper carried out a series of discrete element particle flow numerical simulations with different prefabricated fractures (different number of fractures and fracture angles) based on laboratory rock mechanics tests. The results show that: the overall failure of rock mass is mainly tensile and compressive failure. And, when the crack reaches a certain depth, the influence of primary cracks in rock mass on rock breaking effect will be significantly weakened. Furthermore, in the process of rock breaking, the rock mass basically shows brittle fracture, and the crack initiation stress of rock mass has a good positive correlation with the degree of rock fragmentation. The crack initiation location is often accompanied by stress concentration, which is the key to rock fragmentation. And, the angle of prefabricated cracks will affect the crack initiation position. When the prefabricated crack angle approaches the top angle of the drill, the crack initiation stress will increase. Finally, the fracture mode and initiation mechanism of rock mass are revealed in the process of rock breaking. This study can provide some reference for the optimization of drilling parameters.

Keywords. soft rock, pre-existing fracture, prefabricated crack, crack dip, numerical simulation, fracture mechanism.

1. Introduction
In the field of energy exploitation, fast and effective rock breaking technology is extremely important [1]. To understand the fracture process and fracture mechanism of rock mass, it is necessary to analyze the propagation behavior of cracks in the process of rock fracture [2]. Some scholars have conducted a large number of studies on the fracturing mechanism through experiments, simulations and theoretical analysis [3-4]. Furthermore, the initiation, propagation, and microscopic morphology of fractures were discussed caused by internal and external factors such as different insitu particle heterogeneity, and spatial distribution [5-6].

The microstructure and mechanical properties of soft rock formations are complex [7]. Under the action of external conditions, there are a large number of discontinuities such as microcracks, macrocracks and joints [8]. These discontinuities present great interference to geotechnical engineering activities, especially the drilling process of rock masses. Although many scholars have conducted a lot of research on the drilling process and the fracture behavior of rock masses, there are few researches on the drilling fracture mechanism of soft rock formations with different degrees of fracture. In this paper, the two-dimensional particle flow numerical software PFC is used. Combining with the results of the indoor unconfined uniaxial compressive strength of soft rock samples, the failure mode and initiation mechanism of samples with prefabricated cracks (different number and angle of cracks) under load are discussed. It is expected to provide a certain reference for the improvement of soft rock formation drilling technology.
2. Establishment of Numerical Model

2.1 Laboratory Test

In this test, the high-precision YADW-1000 microcomputer-controlled rock uniaxial testing machine was used to conduct unconfined compression experiments on complete samples of soft rock at the loading speed of 0.1mm/min. The failure characteristics of the specimen were photographed and recorded during the test. According to the final experimental results, the physical and mechanical parameters of the soft rock samples are obtained as shown in table 1.

Table 1. Physical and mechanical parameters of uniaxial compression test

| parameters                         | value |
|------------------------------------|-------|
| uniaxial compressive strength /MPa | 10.8  |
| elastic modulus /10^3MPa           | 8.5   |
| poisson ratio                      | 0.23  |
| density /(g∙cm^{-3})               | 2.68  |

2.2 Calibration of Sample Model Parameters

In the process of conventional finite element numerical analysis, the macroscopic physical and mechanical parameters obtained from laboratory tests can be directly applied to numerical model analysis [9-10]. However, all PFC numerical models need to be calibrated to select appropriate mesoscopic parameters. In fact, this calibration is usually carried out by laboratory uniaxial compression test [11], and the response of the numerical model is directly compared with the indoor test response of the physical material. What’s more, the trial and error method is used to repeatedly adjust the mesoscopic parameters until the mechanical response of the model meets the requirements.

Figure 1. Diagram of parallel bonding model

In this paper, the uniaxial compressive strength test [12] is carried out in strict accordance with the specification, and the parallel bonding model is used to test the numerical soft rock (Fig. 1), in which the contact boundary adopts viscous contact. The friction interface with horizontal shear force can be generated between the sphere and the wall in the viscous boundary, which can reflect the possible friction between the sample and the laminate in the laboratory test to a certain extent. Through the repeated comparison with the indoor experimental results, the meso parameter values in the model are constantly adjusted until the results of numerical simulation are similar or similar to those of indoor experiments (Figure 2). The results show that the uniaxial compressive strength and elastic modulus of the numerical model and the indoor test of soft rock are basically the same (Table 2), and the macroscopic characteristics of the two are in good agreement (Figure 3). At this time, it can be considered that the microscopic parameters of the model meet the calibration requirements. In general, through the comparative analysis of the macro performance of numerical simulation and laboratory experiment, the effectiveness of particle flow numerical simulation in this research direction is effectively illustrated, and the reliability of numerical results is fully proved. Finally, the calibrated mesoscopic parameters (Table 3) are used to establish the numerical model of soft rock samples.

2.3 Design of Numerical Simulation Experiment Scheme

In the relevant literature and software manuals, the cracks of specimens can simulate the joints of rock fracture structure [13]. Since this paper only discusses the mechanical properties and deformation behavior of impact specimens under different number of prefabricated cracks and crack inclination
angles, it is sufficient to achieve the research purpose in a two-dimensional plane with a certain thickness. In this study, the model can be regarded as a three-dimensional sample with a certain thickness. The numerical model of impact test was established according to the PFC particle flow theory. The impact sample is 400 mm in length and 160 mm in width. Clump element is used to generate the impact hammer, and 45kN load is applied to the top of the impact hammer. In order to reduce the adverse impact caused by the shock of stress wave, the model adopts the viscous boundary.

![Stress strain curves of numerical experiment and laboratory test](image1)

Figure 2. Stress strain curves of numerical experiment and laboratory test

![Macro performance of numerical experiment and laboratory test](image2)

Figure 3. Macro performance of numerical experiment and laboratory test

| Table 2. Comparison of experimental mechanical parameters |
|----------------------------------------------------------|
| Numerical Simulation | $E \left(10^3\text{MPa}\right)$ | $\sigma$ (MPa) |
|-----------------------|---------------------------------|--------------|
|                       | 8.4                             | 10.9         |
| Laboratory Test       | 8.5                             | 10.8         |

Based on the above factors, this paper adds different numbers ($n = 0, 1, 2, 3$) and different angles ($\alpha = 30^\circ, 45^\circ, 60^\circ$) of parallel prefabricated fractures (Length=100mm) to establish a complete rock drilling numerical model (Figure 4).

3. **Numerical Simulation of Rock Drilling Under Load**

3.1 Influence of Prefabricated Crack Number on Rock Breaking Effect

In order to analyze the influence of the number of prefabricated cracks on rock breaking effect, this paper sets different number of prefabricated cracks ($n = 0, 1, 2, 3, \alpha = 45^\circ, \lambda = 35$ mm) in the numerical model for simulation calculation. The FISH language embedded in PFC is used to count the generated cracks, and the failure process of the connection key is tracked and monitored according to the parallel key failure criterion. In order to distinguish the type of cracks, the method and shear stress of contact point are calculated by program. When the corresponding stress of axial method reaches the normal stiffness of contact, the crack is marked as tensile crack. If the shear stress reaches the shear stiffness, it is marked as a shear crack. As shown in the calculation results (Figure 5), when the drill bit invades rocks with different numbers of prefabricated cracks under the same load, there are different degrees of stress concentration at the end of the drill bit and at both ends of the prefabricated cracks. With the deepening of the drill bit, fine cracks gradually appear in the dislocation of the particles in the stress concentration area, and the cracks gradually expand, grow and merge, and finally form large cracks and irregular broken cuttings. The whole rock mass shows obvious brittle fracture characteristics.

Compared with other situations, when there is no prefabricated crack in the rock mass (Figure 5 (a)), an approximate symmetrical crack is formed in the whole rock mass during the rock breaking process of the bit, and the depth of the bit intrusion and crack propagation are shallow, and the rock mass fragmentation degree is small, showing better strength characteristics. It is worth noting that, when the number of prefabricated cracks $n=3$, no new cracks are formed around the bottom prefabricated cracks, which may be because a large number of small cracks generated at the top have a dissipative effect on the transmission of stress waves and energy, and the energy load transferred to the bottom is not enough to generate new cracks.

In the process of intrusion, the cracks in the upper part of the rock mass are more abundant than those in the lower part, and tensile cracks and shear cracks appear in the rock mass. The tensile cracks
are dominant, and the shear cracks are only sporadically distributed in the intrusion path of the drill bit (Figure 5). The overall failure of the rock mass is mainly tensile and compressive failure. As shown in Figure 6, when the intrusion load is constant, with the increase of the number of prefabricated cracks in the rock mass, the number of shear cracks remains basically unchanged, and the broken cracks generated by the rock mass are basically linearly increased dominated by tensile cracks. When reaching a certain depth, the influence of prefabricated cracks in rock mass on rock breaking effect will be significantly weakened.

Figure 4. Schematic diagram of number numerical model

Figure 5. Numerical results of different of prefabricated cracks

Figure 6. Curve of crack number

Figure 7. Crack initiation stress curve

The axial force during crack initiation is defined as initiation stress, which reaches the maximum value during rock breaking. According to Griffith strength theory, when the reduction of elastic strain energy stored in the object is greater than or equal to the surface energy required to crack two new surfaces, the crack will expand. At this time, the fracture stress at the fracture end \( \sigma_c = \left( \frac{E \gamma}{4c} \right)^{1/2} \) (where \( \gamma \) represents the fracture surface energy per unit area and \( 2c \) represents the length of the crack). Figure 7 shows that with the increase of the number of prefabricated cracks, the crack initiation stress is approximately linearly weakened, that is, the more broken the rock mass, the smaller the threshold value of the crack initiation stress of the rock mass, the less the fracture surface energy required for rock breaking, and the better the rock breaking effect.

3.2 Influence of Prefabricated Crack Angle on Rock Breaking Effect

In order to analyze the influence of prefabricated fracture angle on rock breaking effect, the prefabricated fractures with angles of \( \alpha = 30^\circ, 45^\circ \) and \( 60^\circ \) (\( n=1, \lambda=35\text{mm} \)) were added into the numerical model respectively for simulation calculation. The fracture morphology of prefabricated fracture specimens with different angles under load breaking is shown in Figure 8. In the process of drilling bit invasion, tensile cracks are also dominated, and there are only sporadic shear cracks. The change of prefabricated fracture angle does not change the fracture mode of rock mass. The calculation results
show that the number of cracks decreases with the increase of prefabricated crack angle, but the overall number changes little.

From the perspective of crack initiation and propagation law, the three groups of samples all crack at the bit contact point, and then generate three groups of obvious main cracks at the stress concentration position. The two groups of main cracks extend to both sides of the horizontal plane and are accompanied by a large number of secondary cracks. The cracks gradually extend and close to form a large number of fine broken rock debris. When the main crack developed along the principal stress direction extended to a certain depth, the crack began to crack from the prefabricated crack, and then developed and grew, and finally merged with the main crack. The crack initiation site at the prefabricated crack is affected by the prefabricated crack angle. When \( \alpha = 30^\circ \), the crack initiation site is fixed to the middle of the crack, and the developed crack is approximately perpendicular to the prefabricated crack (Figure 8 (a)). When \( \alpha = 45^\circ \), a pair of airfoil cracks developed at both ends of the prefabricated crack, and cracks perpendicular to the prefabricated crack developed in the middle (Figure 8 (b)). When \( \alpha = 60^\circ \), an arc-shaped airfoil crack develops at the bottom of the prefabricated crack, and several associated vertical secondary cracks appear in the middle (Figure 8 (c)). On the other hand, as the angle increases, multiple closed circular cracks are developed in the stress concentration area in the middle of the rock mass, forming large broken rock blocks, and the rock fragmentation is improved.

According to the calculation results, although the degree of rock fragmentation and the number of fractures generated increase with the increase of fracture angle (Figure 9), the initiation stress of rock also increases significantly (Figure 10). The analysis shows that, because the bit has a certain top angle, when \( \beta_1 = \beta_2 \), the actual axial stress \( \sigma_1' \) of the maximum principal stress \( \sigma_1 \) acting on the crack reaches the maximum (Figure 11). When the angle of prefabricated crack is close to or equal to the top angle of drill bit 60°, the original crack in rock mass will be compressed and closed, and the initiation stress of rock will be increased in a short time. Once the crack starts at the original crack, the maximum principal stress will act on the newly generated secondary crack. Due to the small angle between the direction of prefabricated cracks and the maximum principal stress, the strength of the main crack extension direction is significantly weakened, and more secondary cracks are produced, and the degree of rock fragmentation will be higher.
**Conclusion**

In this paper, the particle flow software is used to simulate the fracture mode of soft rock samples with different prefabricated cracks (different number and angle of cracks) under load, and the initiation and propagation mechanism of cracks are revealed. The main conclusions are as follows:

1. When the drill bit invades the rock mass, tensile cracks and shear cracks appear simultaneously in the stress concentration part of the rock mass, and the overall failure of the rock mass is mainly tensile and compressive failure. The fracture development in the upper part is more abundant than that in the lower part. When the fracture reaches a certain depth, the influence of the original fracture on the rock breaking effect will be significantly weakened.

2. The rock mass is basically brittle fracture in the process of crushing. With the increase in the number of prefabricated cracks, the threshold of rock initiation stress is significantly reduced, and the rock initiation stress has a good positive correlation with the degree of rock fragmentation.

3. The angle of prefabricated crack will affect the crack initiation position. When the prefabricated crack angle gradually increases, the rock breaking degree will increase and the rock breaking effect will be improved. However, when the crack inclination angle is close to the tip angle of the drill, the crack initiation stress increases significantly.

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