Numerical simulation of damage characteristics of jointed rock under blasting load

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Abstract. In nature, rock masses are often accompanied by joints and weak interlayers. Due to the existence of joints, rock masses are characterized by anisotropy. When the rock mass is excavated by the blasting method, the joints and situ stresses have a great influence on the propagation of the explosion stress wave and the propagation of cracks. In this paper, a two-dimensional finite element model is used to calculate the damage and cracking of jointed rocks under blasting load. Results have shown that the angle between borehole and joint can affect the development of rock crack, and the propagation of stress wave can be suppressed. In addition, it has been verified that initial stress field and its magnitudes of major principal stresses affect the development of the crack zone around the borehole.

1. Introduction

With the development of science and technology, many new methods have been used in tunnel excavation and deep pit operations \cite{1,2}. As a traditional excavation method, the drilling and blasting method has been widely used in field engineering due to its simple operation and low cost. Due to the relatively complex structure of natural rock mass (joints, interlayers and rocks), blasting operations cannot be fully predicted. Coupled with changes in confining pressure at different depths, drilling and blasting are uncontrollable. In engineering practice, engineers usually rely on experience to lay out explosives, which can cause over-excavation or under-excavation of the rock mass.

For a long time, scientific researchers have fully studied the process of rock blasting and have achieved many results. Song et. al \cite{3} simulated porous blasting through model tests, studied the crack propagation process and the law of rock vibration. Combined with self-developed rock constitutive relationship, Sainsbury \cite{4} used numerical calculation methods to obtain the dynamic characteristics of rock damage under blasting load. Xie \cite{5} used the finite element software LS-DYNA to analyse the influence of different initial in-situ stresses on the rock damage and cracking process, and obtained the law of stress wave transmission. Wei \cite{6} used glass instead of rock to carry out a pre-crack blasting model test, and used high-speed camera equipment to record the crack development process. Ju \cite{7} considered the distribution of jointed layers in the rock mass, and analysed the transmission law of stress waves in jointed rocks.

In this paper, a two-dimensional finite element model is used to study the damage characteristics of jointed rocks under different joint angles and different lateral pressure coefficients, and the changes of rock damage areas and the transmission law of stress waves in jointed rocks under the combined action of the two are studied.
2. Model introduction

2.1. Calculation model

In order to study the propagation law of stress wave and rock damage effect in rock mass with weak structural plane, ABAQUS pre-processing module was used to create three joint models with different angles and a comparison model without joints. There are four 2D models in Figure 1. The model size is 3.2 m×1.0 m, the blasthole spacing is 0.8 m, and the blasthole diameter is 0.032 m. And the thickness of rock joints is 0.01 m, and the angles are 45°, 60° and 90°, respectively. Due to the limitation of calculation model size, the infinite boundary element is set on the model boundary to eliminate the influence of reflected wave on the calculation results.

![Numerical models](image)

Figure 1. Numerical models

There are two methods to apply the explosion load: one is the fluid-solid coupling algorithm [8-9]. The Euler element is used to simulate the expansion of the explosive, and the explosion load is passed to the rock element through the contact algorithm, so as to simulate the damage and cracking process of the rock. Another is the equivalent load method [10], which applies the change of explosion load in the form of function to the element at the hole. In this paper, the second method is used to apply the explosive load. By combining Cunningham model [11] and Starfield model [12], according to the blasting parameters such as charge diameter, charge density and decoupling ratio used in the field test [13], the peak value applied on the blasthole wall is 100 MPa, and the load-time function is Equation (1). The curve is shown in Figure 2.

\[ P_t = 4P_b \left( e^{-\beta t} - e^{-\frac{5}{4} \beta t} \right) \]  

(1)
Figure 2. Pressure-time history curves for the selected holes.

2.2. Jointed rock material parameters

The modified Drucker-Prager constitutive model is used to describe the damage evolution process of rock under explosive load. The failure limit of the bearing capacity of the element is defined by setting the threshold of the plastic equivalent displacement of the element or the strain energy \( G \) of the element. The material parameters are shown in Table 1.

| Parameters of rock | Density \((\text{kg/m}^3)\) | Elastic modulus \((\text{GPa})\) | Poisson's ratio | Friction angle \((\text{GPa})\) | Stress ratio \( K \) | Expansion angle | Tensile strength \((\text{MPa})\) |
|-------------------|-----------------|-----------------|-------------|-----------------|-----------------|----------------|-----------------|
| 2600              | 80              | 0.25            | 80          | 0.8             | 10              | 1.0            |                 |
| Cracking strain   | stress rate     | strain rate     | Element failure equivalent plastic displacement \( \bar{e}_f^{pl} \) (mm) |                 |                 |                 |                 |
| 0.0001            | 0.33            | 1E-5            | 0.01        |                 |                 |                 |                 |

Nowadays, many researchers have carried out numerical studies on rock with joints. In their models, the joints of rock are often regarded as a layer of weakened rock and simulated by the same element and constitutive model. The cohesive element is used to simulate the joint layer. The jointed layer is equivalent to a structural layer with small thickness and low strength, and the bilinear damage evolution constitutive model is used to define the brittle fracture mechanical characteristics of the jointed layer. The parameters are shown in Table 2.

| Parameters of weak structural surface model \([14]\) | Density \((\text{kg/m}^3)\) | Normal stiffness \((\text{GPa})\) | Shear stiffness \((\text{GPa})\) | Tensile strength \((\text{MPa})\) | Shear strength \((\text{MPa})\) | Element failure strain energy \( G \) \((\text{N·m})\) |
|-----------------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 2000                                         | 150             | 120             | 0.5             | 0.25            | 0.0015          |                 |

3. The effect of confining pressure on the damage and cracking of jointed rocks

In rock blasting engineering, when the stress wave generated by the explosion load hits the joint layer, the stress wave will be reflected and transmitted, and the amplitude of the stress wave will be attenuated. This situation will make the explosion effect uncontrollable, resulting in over-excavation and under-excavation on the excavation surface. The main purpose of this chapter is to analyze the effect of explosive loads on the damage and cracking of jointed rocks under different confining pressures through a two-dimensional numerical model.

In order to verify the feasibility of the model, the damage and cracking of the jointed rock under the condition of no confining pressure was first calculated. As shown in Figure 3, the angles of joint are respectively 45°, 60°, 90° and without joint for analysis. In double-hole blasting, cracks develop mainly along the blast hole arrangement direction and perpendicular to the blast hole arrangement direction. With the development of cracks, through cracks will be formed between the blast holes. In Figure 3 (b), (c) and (d), the angle between the joint and the horizontal direction has changed, but cracks are generated in the direction perpendicular to the blast hole and the joint plane. This phenomenon is consistent with research results by Qu \([15]\) and Xie \([16]\). When the joint angles are 45° and 90°, the distribution of cracks is closer to the test results of Wop \([17]\), as shown in Figure 4. In the conditions without joint, the horizontal cracks of the rock extend the longest distance. When the angle between the joints and the horizontal direction gradually decreases, the length of the cracks along the horizontal direction gradually decreases. This phenomenon shows that the joints have cracks on the rock under load. And the change of the angle of joints will also affect the direction of rock cracks.
In deep underground foundation pits, rocks usually have higher initial stresses. Therefore, blasting operations may be affected by high vertical ground stress\textsuperscript{[18,19]}. Due to the anisotropic initial stress conditions and the existence of the joint layer, blasting operations will produce two situations. First of all, due to the existence of cracks and joint interlayers near the borehole, the growth and development of cracks under the action of explosives will be affected. The second phenomenon is due to stress concentration around the borehole. In the plane perpendicular to the axis of the blast hole, the difference between the two principal stresses causes the fracture mode to change. The cracks produced by the blast hole tend to develop parallel to the direction of the maximum principal stress.

In order to study the influence of anisotropic initial stress conditions on the development of rock cracks, two sets of loads were applied around the model to simulate the initial stress conditions of the rock, as shown in Figure 5. The applied pressure $P_1=2$ MPa in the X direction and the load $P_2$ in the Y direction are respectively 2 MPa, 1 MPa and 0.5 MPa.
Figure 5. Definitions of the principal components of the initial stresses

As shown in Figure 6, the distribution of cracks around the blast hole in the isotropic initial stress field is relatively uniform, and its trend is similar to the working condition without initial stress, but the area of rock crack distribution is smaller than the crack area without initial stresses. The existence of the initial stresses can inhibit the development of cracks. In the anisotropic initial stress field, the blasting damage zone will produce a strange phenomenon. The cracks along the direction of the maximum principal stress develop larger, while the cracks in the direction of the secondary principal stress will be suppressed. This phenomenon can be explained by a simple model. As shown in Figure 7, the average principal stress of element 1 is the same as the average principal stress of element 2, and the second deviator stress of element 1 is greater than that of element 2. According to the DP constitutive model Yield function, so unit 1 is more prone to tensile failure, and this phenomenon is consistent with the research results [20], and as the difference between the initial stresses in the two directions increases, the crack anisotropy gradually increases.

Figure 6. Effects of in situ stresses on blast induced damage zones
4. Analysis of stress propagation law

When there is a joint layer in the rock, transmission and reflection of the stress wave will occur when the stress wave is transmitted to the joint, and the joint layer will absorb the energy of the stress wave to form cracks. By considering the influence of joint angle and initial stress, the attenuation law of stress wave propagation in jointed rocks is analyzed. As shown in Figure 8, in order to unify the influence of variables on the model, the two units at the leftmost joint of each model are selected as stress observation points. Among them, the point 1 is on the right side of the joint layer, and the point 2 is on the left. They are both 0.2m away from the center of the joint.

\[ T = \frac{\sigma_{P2}}{\sigma_{P1}} \]  

Among them, \( \sigma_{P1} \) is the maximum incident stress amplitude recorded by observation point 1, and \( \sigma_{P2} \) is the maximum transmission stress amplitude recorded by observation point 2.

Figure 9(a) shows the change rule of the transmission coefficient of the stress wave under the isotropic initial stress condition. As the angle between the joint layer and the arrangement direction of the blasthole decreases, the transmission coefficient of the stress gradually decreases. When the angle
is 90°, the transmission coefficient of the stress wave is the largest, indicating that the greater the angle of the joint, the stress wave can easily pass through the joint. The greater the tensile stress in the blast hole arrangement direction after the joint, the greater the joint angle, the greater the probability of cracking along the blast hole line. When the rock mass has initial stress, the transmission coefficients under various working conditions are reduced, indicating that the initial stress will hinder the propagation of explosive stress in the rock.

Figure 9(b) shows the changing law of the transmission coefficient of the stress wave under the anisotropic initial stress condition. Their initial conditions are consistent with those in Section 3. The change of the angle of the joint layer has the same effect on the stress transmittance as that under the isotropic initial stress condition. As the initial stress in the vertical blast hole arrangement direction decreases, the anisotropy of the initial stress field becomes larger, and the stress penetration coefficient in this direction increases. The reason is that the stress wave mainly follows the initial maximum principal stress of the rock. Directional propagation, damage to the unit and formation of cracks, this phenomenon is consistent with the research results [22].

![Figure 9](image.png)

**Figure 9.** Effect of joint angle and initial pressure for transmission coefficient

5. Conclusions

Studying the damage characteristics of jointed rocks and the transmission law of stress waves in jointed rock masses under blast load is of great significance to blasting engineering. In this paper, a two-dimensional plane strain model is used to simulate and analyse the double-hole blasting of jointed rocks. The effect of joint angle and initial stress field on rock damage and fracture, the research results show that:

(1) Under the action of blasting load, the change of the joint angle in the rock will affect the formation and development of rock cracks, and the smaller the angle between the joint and the blast hole arrangement direction, the more obvious the restraint effect on the crack penetration joint.

(2) Under the initial isotropic stress field, as the initial stress increases, the area where the cracks caused by the explosion spread to the surroundings will decrease, and the efficiency of the stress wave through the joints will be suppressed.

(3) Under the initial anisotropic stress field, the cracks caused by the explosion load will tend to the maximum initial stress. The direction of the principal stress is distributed, and the development of cracks in the direction of the secondary principal stress will be suppressed, and the transmission efficiency of the stress wave in the rock will have a corresponding distribution.

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