Numerical study on rock damage characteristics of multi hole blasting

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Abstract. In this study, a two-dimensional finite element numerical simulation method was used to study the damage characteristics of rock mass under multi-hole blasting load. In the analysis, Drucker-Prager constitutive model was used to characterize the strength of rock mass. The stress acting on the blasting hole was simulated by exponential functions, that the stress could reach the maximum value in a short time and then drop to zero in a relative long time. The damage characteristics of rock under different confining pressures, and the influence of free surface on the damage of rock were examined. The results show that under the same blasting load, increasing the confining pressure of surrounding rock can inhibit the development of rock cracks; The free surface made the explosion stress wave reflect, the rock mass between the blasting hole and the free surface produced a phenomenon of stratification crack which restrained the crack propagation below the blasting hole.

1. Introduction
In rock mass excavation projects such as mining, underground transportation, water conservancy and hydropower, blasting is a mainly used rock breaking method due to its high efficiency and low cost. However, rock fragmentation under the action of blasting is a very fast process, which has brought out great challenges to the research on the failure mechanism of rock blasting.
When analyzing the response of underground rock under blasting or other dynamic loads, rock damage is affected by its strength grade, initial stress condition and the distance between the blasting hole and free surface. It is difficult to clarify a complete and accurate theory of rock blasting damage clearly. On the other hand, it is very expensive and inconvenient to study rock blasting by laboratory tests or in-situ tests. With the development of computer, numerical simulation has become one of the main methods to study rock blasting damage. The purpose of this study is to use two-dimensional numerical simulation method to establish a simple explosion damage analysis model, and calculate the process of multi-hole blasting of rock under the condition of decoupling charging using the software of ABAQUS.

2. Brief description of Model
In this study, a two-dimensional plane strain model was used to simulate the rock blasting through the finite element software ABAQUS. In the numerical analysis, the Drucker-Prager constitutive model [1] and the plastic damage model were used to describe the development of the cracks in rock, and the explosion load in the form of decoupling charging was applied equivalently through the exponential function. The infinite boundary element was set to absorb the energy wave transferred to the boundary.

2.1. Plastic damage model
In order to meet the needs of engineering practice and ensure the accuracy of calculation, the modified Drucker Prager constitutive model was selected to calculate rock. The yield function is given by the following equation:

\[ F = t - p \tan \varphi - d = 0 \]  \hspace{2cm} (1)

Where \( p \) is the average principal stress of the element and \( d \) is the cohesion of the rock. The tensile yield criterion adopted in this study is given by the following equation: \( d = \left( \frac{1}{K} + \frac{1}{3} \tan \beta \right) \sigma_t \), where \( \beta \) is the friction angle, \( \sigma_t \) is the uniaxial tensile stress, and \( t \) is the stress state parameter. The expression is as follows:

\[ t = \frac{1}{2} q \left[ 1 + \frac{1}{K} - \left( 1 - \frac{1}{K} \right) \left( \frac{r}{q} \right)^{1/3} \right] \]  \hspace{2cm} (2)

Where \( q \) is the equivalent deviator stress, \( K \) is the ratio of triaxial tensile strength to triaxial compressive strength, which is generally 0.778–1.0. When \( K=1.0 \), the yield surface is a circumscribed circle, and \( r \) is the third invariant of deviator stress.

The plastic potential energy function of the constitutive model of rock is as follows:

\[ G = t - p \tan \psi \]  \hspace{2cm} (3)

Where \( \psi \) is the expansion angle of rock. The calculation parameters of the modified Drucker Prager constitutive model for surrounding rock are based on the tests of rock material parameter and geological report in the mountain tunnel of Zhuhai Xingye Express Way. The specific data are shown in Table 1.
In order to describe the damage evolution process of rock element under blasting load, the damage evolution criterion-shear damage was adopted in this study. The ultimate bearing capacity of the element is defined by setting the value of plastic equivalent displacement $\bar{u}^{pl}_f$ or strain energy of the element.

$$\sigma_y = (1 - D) \bar{\sigma}_y$$

Where, $\sigma_y$ is the current stress tensor of the element, $\bar{\sigma}_y$ is the stress tensor of the element without damage, and $D$ is the total damage factor of the element. The calculation method is as follows:

$$D = \max \left\{ d_{\text{mult}}, \max_{j \in N_{\text{max}}} (d_i) \right\}$$

Where, $d_i$ is the element damage factor caused by a single variable (eg: tensile failure, compressive failure or shear failure), and $d_{\text{mult}}$ is the element damage factor caused by multi variables. The calculation method is as follows:

$$d_{\text{mult}} = 1 - \prod_{i=1}^{N} (1 - d_i)$$

$$d_i = \frac{L \bar{\varepsilon}^{pl}_i}{\bar{u}^{pl}_f} = \frac{\bar{\varepsilon}^{pl}_i}{\bar{u}^{pl}_f}$$

The variables to determine damage used in this study is equivalent plastic strain $\bar{\varepsilon}^{pl}$

$$\bar{\varepsilon}^{pl} = \sqrt[3]{\frac{2}{3} (\varepsilon^{pl} : \varepsilon^{pl})}.$$

Where, $L$ is the element length, $\bar{\varepsilon}^{pl}$ is the equivalent plastic strain of the element, $\bar{u}^{pl}_f$ is the equivalent plastic displacement of the current element and $\bar{u}^{pl}_f$ is the equivalent failure plastic displacement for the element. When $0 < \bar{u}^{pl}_f < \bar{u}^{pl}_f$, it is considered that the damage begins to

| Table 1. Material parameters of rock |
|-------------------------------------|
| Density (kg/m$^3$) | 2600 | Poisson's ratio | 0.25 |
| Elastic modulus (GPa) | 140 | Stress ratio $K$ | 0.8 |
| Failure strain | 0.006 | Strain rate | 1E-5 |
| Stress Rate | 0.33 | Internal friction angle($\phi$) | 80 |
| Dilatancy angle | 10 | Tensile strength (MPa) | 3.0 |
| Element failure equivalent plastic displacement | 0.0006 |

$$\varepsilon^{pl} \quad \varepsilon^{pl} \quad \varepsilon^{pl} \quad \frac{2}{3} (\varepsilon^{pl} : \varepsilon^{pl})$$
accumulate; When \( \bar{\textit{n}}^\mu = \bar{\textit{n}}_i^\mu \), \( d_i = 1 \) unit, the element is considered to have completely failed and quit the operation.

2.2. Blasting load and boundary conditions

After the explosive is detonated, the gas in the blast hole is extruded, expanding and then acting on the rock of the wall of the hole. The rock cracks under the action of extrusion. At the same time, the high-pressure gas is discharged rapidly from the blast hole and cracks, and the pressure of the blast hole decreases rapidly. In order to accurately simulate the effect of explosion load on rock, there are mainly three methods at present: (1) The fluid solid coupling algorithm is used to calculate the contact stress of rock caused by explosive expansion. E.g., Xie et al. [2-3] and Ye & Liu [4] used ALE algorithm in nonlinear finite element software LSDYNA to simulate the interaction between explosive gas and rock. Goel et al. [5] and Zaid et al. [6] used CEL algorithm in ABAQUS to simulate the expansion process of explosive gas. In their simulation, eulerian element was used to simulate the expansion process of explosive gas, solid element was used for rock, and general contact algorithm was used to simulate the interaction behaviour. This method relies heavily on the grid of model elements and has some limitations; (2) Discrete element method is used to simulate the damage and cracking characteristics of rock under explosion condition. The discrete element method provides a new method to simulate the deformation of objects under explosion and impact loads. In the simulation of rock blasting, the discrete element method can well describe the process of explosive explosion and rock damage cracking due to its advantages [7, 8]; (3) The pressure data collected from field tests are used to fit the empirical formula [9,10], and the time history relationship of detonation pressure is loaded on the surface of rock element around the blast hole in the form of load function. In order to accurately simulate the propagation of stress wave in rock at the late stage of explosion, the non-reflecting boundary is used at the boundary of the model to absorb the transferred energy wave. This method can effectively eliminate the influence of boundary reflection wave on the whole calculation of the model, and was selected in the present study.

2.2.1 Application method of blasting load

Under the blasting load, the damage degree of rock is related to the amount of explosives placed in the blasting hole and the energy released by each explosive. The greater the pressure in the blasting hole, the more serious the damage of rock. Two basic forms of energy are released when an explosive reacts. The first type of energy is called as shock energy and the second one is called as gas energy. This released energy generates a stress wave loading that travels outward from the explosion cavity followed by a long duration of gas pressure loading. Numerical results obtained by some research indicated that only the modelling of the stress wave propagation could give reasonable prediction of rock mass response to blasting load [11-13]. Although the explosion load has a great influence on the degree of rock cracking, the method of direct measurement through experiments is limited. In order to solve this problem, various empirical formulas or detonation theories were used for the study. In engineering practice, in order to make it easy to fill explosives, decoupling charging is generally used. Under the condition of decoupling charging, the gas load generated in the blast hole is half of the explosive load [14]. The parameters of emulsion explosive used in this study were obtained according
to the test results of Vanbrabant et al. [15], and the peak explosion load was calculated according to the decoupling charging conditions, as shown in Table 2.

**Table 2. Calculation parameters of the peak blasting load**

| Un-reacted explosive density (kg/m³) | The explosion wave velocity (m/s) | Peak blasting load (GPa) |
|-------------------------------------|----------------------------------|-------------------------|
| 780                                 | 4052                             | 1.6                     |

In order to continuously and efficiently describe the time history of blasting load released by the explosion, this study used the exponential function proposed by Starfield & Pugliese [16] to perform fitting calculations, as shown in equation (9)

\[ P_t = 4P_0 \left( e^{-\beta t} - e^{-\sqrt{2} \beta t} \right) \]  

(9)

Where \( P_t \) is the value of the blasting load, \( t \) is the time and \( \beta \) is damping parameter, where the damping parameter can be calculated by the time \( t_r \) when the explosion load reaches the peak value, using a specific calculation formula \( \beta = \sqrt{2/\ln(1/2)/t_r} \). According to a large number of literature assumptions and measured data, it is shown that the time of the peak of the explosion pressure varies from a few microseconds to more than 100 microseconds after the explosion. The reason is the difference in the types of explosives [17]. This study calculated the time history curve of explosion peak load with \( t_r=50\text{us} \) and \( 150\text{us} \), respectively. As shown in Fig. 1, the time history of explosion load with \( t_r=50\text{us} \) was selected as the load value and applied to each blast hole in the finite element model. On the surface of the surrounding elements, the damage characteristics of the rock under the condition of decoupling charging were analyzed, the time interval of calculation and analysis is set to be 1ms to analyze the whole process of the blasting load.

**Fig. 1. Time history of blasting load curve**
2.2.2 Boundary conditions
A variety of infinite boundary elements are embedded in the dynamic calculation module incorporated in the ABAQUS software. In this study, a four-node infinite boundary element (CINPE4) is used to simulate the non-reflecting boundary to eliminate the reflection or refraction when the stress wave propagates to the model boundary. Therefore, in the numerical simulation, except for the surface (upper boundary), the other three boundaries all use infinite boundary elements. The model is shown in Fig. 2.

![Fig. 2. Boundary conditions of the model](image)

3. Calculation results
In this study, the confining pressure and the distance between the blasting hole and the free surface were selected as influence factors to analyze the porous blasting on the damage characteristics of the rock. In order to make a comparison, two plane strain calculation models were built for comparison and discussion. The models are shown in Fig. 3. In the figure, the length and width of the two models are the same, which are 5 m of length and 3 m of width. Four blastholes with a size of 0.08m are arranged. The distance between the blastholes is 0.8 m, and the distance between the left and right boundary sides is 1.3 m. In order to analyze the impact of the explosion on the free surface, the distance between the blastholes and the free surface was used as a variable, and infinite elements are applied to the boundary of the non-free surface to act as a nonreflecting boundary.

![Fig. 3. Simulation model of multi-hole blasting](image)

(a) Free surface is provided  
(b) Free surface is not provided
There are many different theories to explain the mechanism of rock breaking caused by blasting, but the widely accepted method is the three-section method \[18\] that divides the affected area into fragmentation zone, fracture zone and elastic zone. In the fragmentation zone, the radial compressive stress produced by shock wave in the first region exceeds the dynamic compressive strength of surrounding rock, and expands into complete fracture with failure of rock compression, therefore, the area is also called the crushing zone. The second area is known as the fracture zone in which the rock breaks due to high tangential stress. The third area is elastic zone. Since the energy released by explosion consumes a lot of work in the first two areas, the stress wave is attenuated sharply in the rock, and plastic damage in the rock far away from the explosion point will not occur.

Fig. 4 shows the damage distribution of rock under confining pressure of 0 Mpa, 20 MPa and 50 MPa, respectively. When the blasting load begins to act on the rock around the blasting hole, and the value of the load has reached the damage strength of the rock, the rock around the blasting hole will be damaged first. When the stress wave starts to transfer outward, the damage of the rock around the blasting hole will be further intensified and the rock gradually fails. The fracture area also can diffuse to the outside with the transmission of stress wave. Under the interaction of multi-hole blasting load, the rock damage between the blasting holes was more serious, and the case of penetration occurred. Under the action of different confining pressures, the damage of rock was different. In Fig. 4 (a), under the condition of no confining pressure, the rock fragmentation area and cracking area was larger, while under the confining pressure of 50 MPa, the fragmentation area and cracking area was obviously reduced.

![Damage Distribution](image)

**Fig. 4.** Damage distribution of surrounding rock under different confining pressures

In order to describe the change of the damage area more intuitively, the area of the element damage factor \(d=0.6-1.0\) in the entire model was extracted, and the rock damage was described by the ratio...
between the damage area and the total area as shown in Fig. 5. In the initial stage, the damage ratio of the rock increased rapidly, but in the later stage, the increase rate was relatively slow. Under the three confining pressure conditions, the final ratios of rock damage area were 0.0446, 0.0382 and 0.0222, respectively. The reason is that when the initial confining pressure was applied on the rock, the strength to produce plastic deformation increased, in other words, under the same loading conditions, plastic strain was more difficult to appear, so that the deformation was reduced, and the expansion of rock damage area was restrained.

**Fig. 5.** The change of the rock damage area under different confining pressures

**Fig. 6.** Damage distribution of rock with different distances between the blast hole and free surface

During the blasting in rock mass, the internal conditions such as cavity, joint and soft zone can be regarded as free surfaces. The existence of these free surfaces cannot be neglected in the transmission
of waves and the expansion of cracks. The distance between the blasting hole and the free surface in the model was 0.5 m and 1.5 m respectively. As shown in Fig. 6, there were many cracks on one side of the free boundary of rock, and most of them were layered cracks parallel to the free surface. By increasing the distance between the blasting hole and the free surface, the damage degree of the crack was weakened, but the radiation range of the stress wave generated by the explosion increased, therefore, when the distance was 1.5 m, the damage area of the rock was larger than that in the case of 0.5 m distance.

4. Conclusion
In this study, a two-dimensional plane strain model was adopted to model the muti-hole blasting of the rock, and the blasting load is equivalent to an exponential function and loaded on the surface of the rock element around the blasting hole. The damage characteristics of muti-hole blasting rock were analyzed under different confining pressures. The following conclusions can be obtained.
(1) In the multi-hole blasting, the cracks around a single blast hole presented a net-like distribution, and the rock along the direction of the blasting arrangement was more severely damaged, and penetration cracks formed between the blasting holes.
(2) Under the same condition of explosive loads, increasing the confining pressure of the surrounding rock, the strength requirements for producing plastic strain to the rock also increased, thereby inhibiting the development of rock cracks.
(3) The free surface had a great influence on the propagation of blasting cracks. The main reason was that the free surface would reflect the explosion stress wave, causing the rock mass between the blasting hole and the free surface to spall. This horizontal cracks inhibited the propagation of cracks below the blast hole. This phenomenon could be alleviated by increasing the distance between the blasting hole and the free surface, but quantitative analysis needs to be carried out in further research.

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