Research on Blasting Fragment Distribution and Parameter Optimization of Open-Pit Mines Based on FDEM

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Abstract. This study employs the Finite-Discrete Element Coupling Method (FDEM) to simulate and optimize the blasting process in open-pit mines, focusing on the fragmentation distribution and key blasting parameters. The FDEM, which integrates the finite element (FE) and discrete element (DE) methods, provides a comprehensive approach to simulate the initiation, propagation, and coalescence of cracks in rock materials under external loads. The research utilizes field monitoring data from Zijinshan Gold and Copper Mine, encompassing stress waves, vibration velocities, and blasting block distributions during the blasting process. Numerical simulation results were generated using Open-FDEM software to model the fracture patterns and stress distributions under blasting loads, facilitating a detailed analysis of blasting effects. The geometric model constructed for the simulation represents a specific grade of rock step blasting in the Zijinshan open-pit mine, with adjustable parameters such as the chassis resistance line, plugging length, and charge amount to analyze their impact on blasting outcomes. The study also investigates the influence of the explosion load on the fragmentation process, identifying an optimal load value that minimizes large rock formation and maximizes the efficiency of ore crushing.

Keywords: Finite-Discrete Element Coupling Method (FDEM); Open-Pit Mining; Blasting Fragment Distribution; Parameter Optimization; Slope Stability.

1. Introduction

With the rapid development of global industrialization and urbanization, the demand for mineral resources continues to grow. Open-pit mining, as an important method of mineral resource exploitation, has a significant impact on economic development and engineering safety in terms of mining efficiency and safety. Blasting operations, as a key step in open-pit mining, directly affect the production capacity and economic benefits of mines. Therefore, in-depth study of the blasting process in open-pit mines, optimization of blasting parameters, and improvement of blasting efficiency are of great significance for achieving sustainable development of mines [1].

This study takes the Zijinshan Gold and Copper Mine as an example and uses FDEM simulation technology to conduct in-depth numerical simulation analysis of the single-hole step blasting process [2]. By meticulously studying the characteristics of the blasting block distribution and combining actual engineering needs, the blasting parameter combination is optimized. A prediction model between the peak particle vibration velocity and the block qualification rate is established in the study, and a large amount of blasting data is analyzed using machine learning algorithms to further improve the accuracy of the prediction model. In addition, this study also explores the risk factors that may affect the stability of the slope during the blasting process, providing technical support for the safe production of mines.

2. Model Preparation

2.1. Data processing

The data in this paper come from the field monitoring data collected directly from the blasting activities of Zijinshan Gold and Copper Mine, including the key indicators such as stress wave, vibration velocity and blasting block distribution during the blasting process. The numerical simulation results are obtained by using Open-FDEM software to simulate the fracture mode and stress distribution of rock under blasting load. A more extensive data comparison and trend analysis are carried out using the open blasting engineering statistical database.

2.2. FDEM

Proposed by Munjiza et al., combining the advantages of finite element (FE) and discrete element (DE) methods, the whole process of crack initiation, propagation, penetration and failure of rock materials under external loads can be simulated [3]. In FDEM, the simulated object is discretized into a grid of nodes and triangular units. An initial thick-less quadrilateral joint element acting as a bond is inserted between two adjacent triangular elements. Only elastic deformation occurs in triangular element. Generalized Hooke's law is used to calculate Cauchy stress after deformation. The quadrilateral joint element can undergo plastic deformation and failure, and its tensile stress and shear stress can be determined according to the stress-opening relationship [4].

In order to simulate the mechanical response of layered rocks under external loads, Lisjak et al. proposed a dispersion method [5]. In this method, the bedding plane of the rock is explicitly characterized, and the grid topology of the material within the layer is divided by random triangular elements. Liu Ping et al. proposed that when the displacement of the joint element reaches the corresponding limit displacement, the joint element breaks and the triangular elements on both sides begin to contact [6].

FDEM uses an efficient NBS (no binary search) contact retrieval algorithm and a contact force calculation method based on potential function. In this paper, the influence of blasting vibration velocity is obtained based on FDEM method, and the prediction expression of peak vibration velocity is derived which is suitable for the topography of Zijinshan step.

2.3. Model initial parameter

The experimental data and field monitoring data were used to calibrate the model parameters, and the mesh size in the FDEM model was optimized. The local encryption method was used to improve the resolution of the mesh near the burst source, while considering the calculation efficiency. Conduct numerical simulation and adjust the model parameters until the simulation results match the actual blasting effect, such as the blasting block distribution.

According to the specific geological conditions and blasting engineering requirements of Zijinshan open-pit mine, key rock mechanics parameters, such as elastic modulus, Poisson's ratio, density, cohesion and internal friction Angle, as well as material property parameters of explosives, including density, detonation velocity, charge diameter, volume modulus and shear modulus, should be determined in the study. In the simulation of blasting process, the blasting load is applied by the pressure function, and the rise time, peak stress and decay rate of the load are defined to accurately simulate the influence of blasting on the mine slope.

2.4. Basic governing equations of nodes

In Finite Difference Electromagnetic numerical simulation (FDEM), explicit time integration is usually used to solve dynamic nodes. This method is suitable for dealing with transient problems and can avoid solving nonlinear equations directly in the implicit method, as shown in Fig. 1.

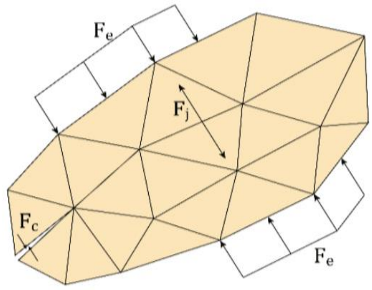

Fig 1. Schematic diagram of forces at nodes.

The basic governing equations of the nodes are shown below.

$$v_{n+1} = v_n + \Delta t \bullet a_n \ . \tag{1}$$

Where v_{n+1} the speed on the new time step is, v_n is the speed on the current time step, a_n is the acceleration on the current time step, and Δt is the time step.

$$\overrightarrow{M}\ddot{x} + \overrightarrow{C}\dot{x} = \overrightarrow{F}(x) \ . \tag{2}$$

$\overrightarrow{M}$ And $\overrightarrow{C}$ are the mass matrix and damping matrix of all element nodes in the system respectively, $\vec{x}$ is the displacement vector, and $\vec{F}x$ includes ($\overrightarrow{F_c}$ $\vec{F}_d$ $\vec{F}_j$ $\overrightarrow{F_e}$) represents the unbalanced force vector of the node. Where $\overrightarrow{F_c}$ represents the contact force assigned to the node by the discrete element, $\vec{F}_d$ represents the joint force caused by the elastic deformation of the triangular element, $\vec{F}_j$ represents the force assigned to the node by the binding force of the joint element, and $\overrightarrow{F_e}$ represents the force assigned to the node by the external load

The damping matrix is used in numerical simulation to prevent the stress oscillation of the model, accelerate the equilibrium and ensure the accuracy of the result. The expression is as follows.

$$C = \mu\vec{I} \ . \tag{3}$$

Where µrepresents the damping coefficient and C represents the identity matrix.

For homogeneous isotropic materials, the relationship between stress and strain follows the linear elastic theory, and the commonly adopted constitutive relationship can be simplified as follows:

$$\sigma = E\varepsilon \ . \tag{4}$$

Where σ represents the stress tensor,E represents the elastic modulus of the material (also known as Young's modulus), and ε represents the strain tensor

When calculating the deformation of a triangular element, because the internal stress of the element is consistent, the equivalent nodal force on the boundary of the element can be directly obtained:

$$\overrightarrow{f_n} = \frac{1}{2}\vec{T}\overrightarrow{ne}l = \frac{1}{2}\begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{bmatrix}\begin{bmatrix} n_x \\ n_y \end{bmatrix} l \ . \tag{5}$$

Where $\overrightarrow{ne}$ the outer normal unit is vector of the side of the triangular element, and l is the side length of the side of the element

3. Model Construction

3.1. Geometric model construction

The rock step blasting of a certain grade in Zijinshan open-pit mine is simulated and studied. The dimensions of the model include the step height of 16m, the step depth of 24m, the lateral width of 18m, the slope Angle of 75°, the diameter of the gun hole of 165mm and the super depth of the gun hole of 2m. By adjusting the chassis resistance line, plugging length and charge amount, how they affect the blasting effect is analyzed. The blasting opportunity model of single-hole slope is shown in Fig. 2.

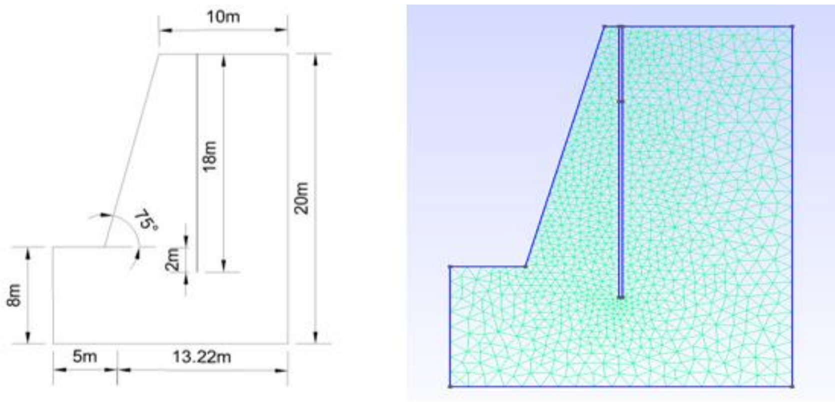

Fig 2. Blasting geometry model of single hole slope.

In the simulation, it is assumed that the medium is a uniform and unstressed material, and the plugging material is different from the rock material. The interior of the model should be filled with mesh cells, with high mesh density near the hole (0.1) and low mesh density in other areas (0.5).

3.2. Material parameters

According to the investigation, the rocks in Zijinshan open-pit mining area are mainly medium-fine grained granite. Through rock mechanics tests, specific parameters of rock materials are obtained, as shown in Table 1.

Table 1. Mechanical parameters of medium and fine-grained granite.

Rock sample	Elastic modulus (GPa)	Poisson's ratio	density (g/cm3)	cohesion (MPa)	angle of internal friction
Medium fine grained granite	16	0.28	2.7	6.43	45.65

No. 2 rock emulsion explosive is mainly used for slope blasting in mining area, and its material parameters are shown in Table 2 below.

Table 2. Explosive material parameter.

density ($kg \cdot m^{-3}$)	detonation velocity (m/s)	charge diameter (mm)	volume modulus (K)	shear modulus (G)
1200	4000	130	0	0

The blast force of explosive is regarded as the force concentrated in the center of the hole, and the loading characteristics of this force can be described by the rise time, peak stress and decay rate.

3.3. Gaussian function curve fitting of blasting block

In this paper, Gaussian fitting is used to process and analyze the experimental data. Gaussian fitting is a nonlinear fitting method that fits data based on a Gaussian function (normal distribution function). The Gaussian function has a symmetrical bell curve, which can describe the peak value in blasting experiment data well.

The Gaussian function is a very important probability distribution in statistics, which can describe the center of the data and the degree of dispersion by means of the mean (μ) and the standard deviation (σ). In the field of blasting engineering, the fitting of Gaussian function can predict the block distribution of rock after blasting. Through the analysis of the block data obtained from the blasting experiment, the logarithmic data points are fitted by using the mathematical model of Gaussian function. The results of Gaussian function fitting enable us to precisely adjust the blasting parameters to achieve the best blasting effect. By adjusting the chassis resistance line, plugging length and explosion load, the rock breaking mode can be effectively controlled and the blasting scheme can be optimized.

4. Experiment

4.1. Chassis resistance line

After simulating three sets of blasting models with different chassis resistance line values, ParaView software was used to show the change of rock blasting over time. Especially for the model with a chassis resistance line of 5m (the result is the same for the model with a resistance line of 5.81m), the crushing condition of the rock after blasting, the size of the blasting block, the grading rate and the shape meet the engineering requirements, and the blasting breakage does not exceed the design range, and the parameter diagram with a good effect is obtained. For details, see Fig. 3. When the resistance line is 6.6m, the drilling cost will be increased, the blasting efficiency is low, more large rocks will be produced, the workload and cost of subsequent treatment (such as secondary crushing) will be increased, and unbroken rocks (base) will be formed at the bottom of the blasting area, increasing the risk of flying stones. See Table 3 for details.

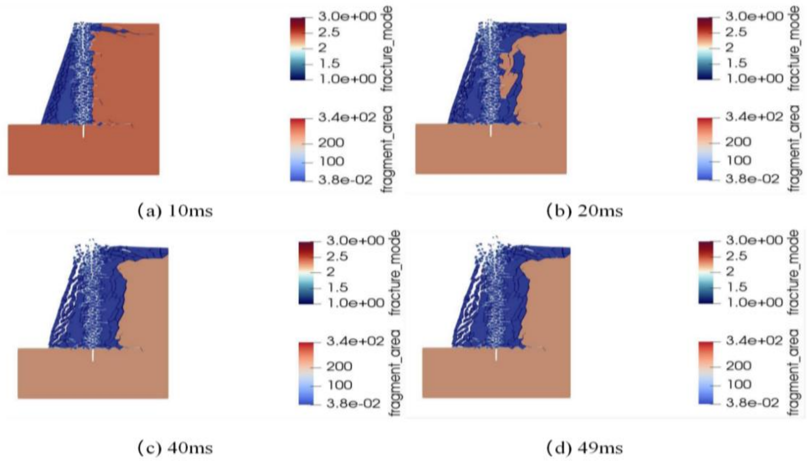

Fig 3. The demolition zone when the chassis resistance line value is 5m.

Table 3. Statistics of average blasting block quantity of different chassis resistance line lengths.

Chassis resistance line (m)	Average lumpiness (m^2)				
	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
5.0	1095	432	183	66	24
5.81	1095	432	183	66	24
6.6	359	127	89	21	21

4.2. Plugging length

When the plugging length is set to 6.0m, the blasting effect is good, the direction of blasting energy release can be effectively controlled, and the expected blasting effect can be achieved. Reduce the flying stones produced during blasting, improve the safety of operation, and the degree of rock breakage after blasting is better. On the other hand, 5.5m plugging length blasting produced more chunks, as shown in Table 4. The simulated cloud diagram of the maximum principal stress changing with time during the blasting process is shown in Figure 3-5. The threshold range of blasting simulation test data when the plugging length is 6.0m is set as (0.04~1m). Within this set size range, the crushing zone near the hole can be obtained, so as to facilitate the statistics and data fitting of the blasting crushing block degree, as shown in Fig. 4.

Table 4. Statistics of average blasting block quantity of different chassis resistance line lengths.

Chassis resistance line (m)	Average lumpiness (m^2)				
	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
5.0	366	134	92	33	31
5.5	234	107	60	54	17
6.0	378	155	89	86	44

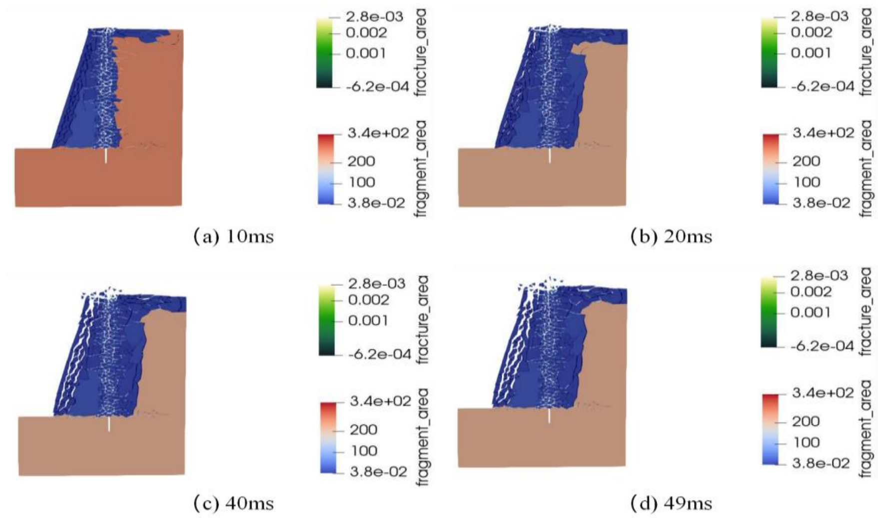

Fig 4. The blasting crushing zone when the plugging length is 5m.

4.3. Explosion load

Two sets of experimental conditions were designed, respectively corresponding to different explosion load values (0.6GPa, 1.2GPa, 1.6GPa, 2.8GPa). The research found that data errors would occur when the load was set above 3.0GPa. The experimental results are shown in Table 5.The influence of explosion load on blasting block distribution and overall crushing effect is deeply analyzed. It is obtained that when the explosion load of the model is 2.0GPa, the blasting effect reaches the best state, the generation of large rocks is reduced, the blasting block is small, and the crushing quality of the ore is improved and the subsequent processing efficiency is improved, as shown in Fig. 5.

Table 5. Statistics of blasting average block quantity of different plugging lengths.

Chassis resistance line (m)	Average lumpiness (m^2)				
	0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0
0.6	231	60	55	34	27
1.2	414	157	77	70	26
1.6	378	155	89	86	44
2.0	592	175	62	48	41
2.8	414	157	77	70	26

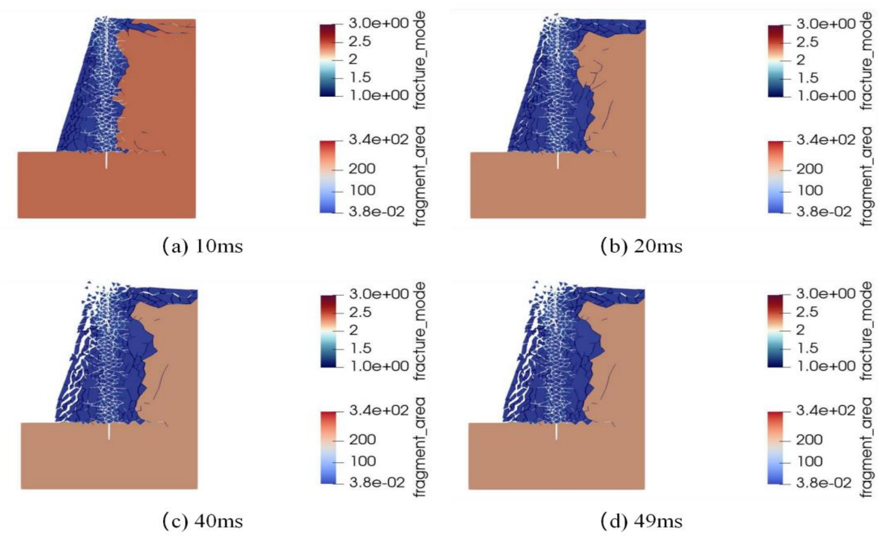

Fig 5. The blast crushing zone under the explosion load of 2.0GPa.

Through the simulation analysis of the rock step blasting in Zijinshan open-pit mine, it is concluded that the optimization of the resistance line of the base is important for controlling the rock size and reducing the root phenomenon after blasting. Through simulation analysis, it is found that the better blasting effect can be obtained when the chassis resistance line is set to 5m. When the plugging length is 5.0m, it is the best choice. When the explosion load value is set to 1.2GPa, the blasting block distribution is small and uniform, and the blasting efficiency is the highest. The explosive pile has a good shape, which is conducive to subsequent shovel loading and transportation. The optimum parameter combination of step blasting in Zijinshan open-pit mine is obtained comprehensively.

5. Conclusion

This study conducted an in-depth numerical simulation analysis of the single-hole step blasting process at the Zijinshan Gold and Copper Mine open-pit using the Finite-Discrete Element Coupling Method (FDEM). The results indicate that FDEM, as a powerful numerical simulation tool, can effectively simulate the mechanical behavior and fragmentation patterns of rocks during the blasting process, providing theoretical foundations and technical support for the optimization of open-pit mine blasting parameters. Future work will continue to explore the application of FDEM under more complex geological conditions and further integrate multidisciplinary technologies to achieve more accurate and automated optimization of blasting parameters.

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