

Article

Fracture and Damage of Slit Charge Blasting in the Layered Rock Mass

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Abstract: Directional fracture blasting technology of the slit charge has broad application prospects in the drilling and blasting construction of the layered rock mass. In this paper, the method of model experiment and numerical simulation is used to preliminarily explore the fracture damage characteristics of slit charge blasting in the layered rock mass. The results show that the blasting effect of the slit charge in the layered rock mass is significantly different from that of the unlayered rock mass, and the pressure relief of the blasting gas at the layer is the main factor affecting the blasting effect. The length of directional cracks in the slit direction is significantly larger than that in other directions, and the directional fracture effect of the slit charge in the layered rock mass can still be played well. However, both the directional crack length and the damage range of rock mass in the slit direction gradually decrease along the detonation direction. In addition, the damage value of a single-layer rock mass also decreases gradually along the detonation direction. In engineering practice, the directional fracture effect of the layered rock mass can be improved by detonating at both ends of the slit charge at the same time.

Keywords: layered rock mass; slit charge; blasting; fracture; damage



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1. Introduction

The drilling and blasting method realizes rock fragmentation through mechanical drilling and explosive blasting and has consistently been an important construction method in related fields, such as geotechnical engineering [1–3] and mining engineering [4–6]. In response to different roadway excavation needs, many new blasting technologies have been developed in recent years, such as, multi-stage cut blasting technology [7], large hole cut blasting technology [8], slit charge blasting technology [9,10], etc. Among them, as shown in Figure 1, slit charge blasting technology is widely used in the peripheral forming control of roadways due to its characteristics of directional fracture, flexible construction, and wide application range. The slit charge mainly comprises two parts: the slit tube and the explosive. The slit tube is prefabricated with slits. After the explosive is detonated, the blasting energy is mainly released along the slit direction to realize the directional fracture of the rock mass. Engineering practice shows that the application of slit charge blasting technology in hard rock and the unlayered rock mass can effectively control overbreak–underbreak, reduce surrounding rock damage, and ensure peripheral forming quality [11,12].

Most of the rock roadways in coal mines are in sedimentary rock strata, and the rock mass is mostly distributed in layers with poor integrity. The fracture damage of the layered rock mass under a blasting load is the result of the combined action of blasting stress wave and blasting gas [13]. When blasting is carried out in the layered rock mass, the blasting

energy is easily released in advance along the interlayer gap, and the energy utilization efficiency is low, resulting in a poor blasting effect. Relevant scientific researchers have carried out research on this. Among them, Wang et al. [14] found that the difference in the wave impedance of the layered medium of the layered rock mass will determine the distribution of blasting energy and ultimately affect the shape of the blast cavity. The research results of Song et al. [15] also show that the layered interface of the layered rock mass affects the formation of the blast cavity. In addition, Hu et al. [16] pointed out that the reflection effect of blasting stress waves in the layered rock mass has a significant effect on blasting damage. Frequency response characteristics of blasting vibration in the layered rock mass are also quite different from those of the unlayered rock mass [17]. In addition, due to the weak interlayer bonding force of the layered rock mass, blasting excavation is likely to cause the rock layer to peel off, resulting in a large area of overbreak, which seriously affects the roadway forming quality [18].

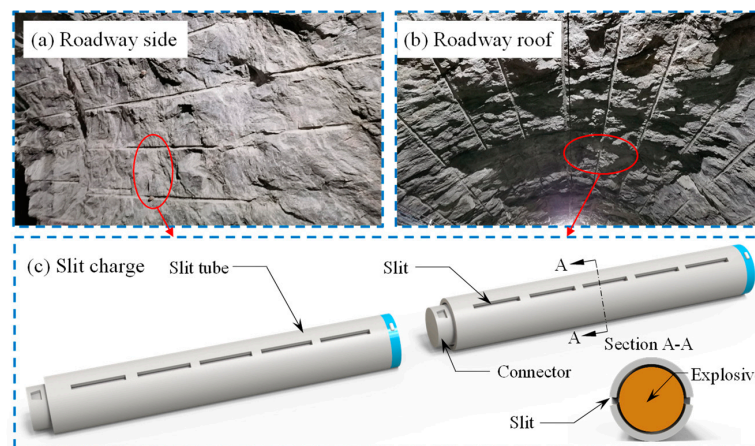


Figure 1. Structure and engineering application of the slit charge.

It can be found that the research on the mechanism of a typical charge of blasting in the layered rock mass has received extensive attention from scientific researchers and provides scientific guidance for the optimization of blasting parameters in engineering practice. At the same time, as a blasting technology widely used in roadway excavation, the effectiveness of the directional fracture of the slit charge in the unlayered rock mass has been generally recognized. The engineering application of the slit charge in the layered rock mass has a huge market prospect, and the basic theoretical research on slit charge blasting in the layered rock mass deserves attention. However, there are few relevant research reports on slit charge blasting in the layered rock mass. Based on this, this paper intends to conduct an exploratory study on the fracture and damage of slit charge blasting in the layered rock mass by means of model experiments and numerical simulation.

2. Model Experiment Design and Parameters

The blasting stress wave and blasting gas generated by explosive detonation are the main driving forces for rock fragmentation. Slit charge blasting mainly uses the slit tube to control the release direction of the blasting gas to achieve directional fracture. The essence of the slit charge is a strip-shaped charge. In the unlayered rock mass, the stress wave generated by the blasting of the strip-shaped charge will propagate in the form of a cylindrical wave. As shown in Figure 2, in the layered rock mass, when the angle between the detonation direction of the strip-shaped charge and the layer is 90° , the propagation process of the blasting stress wave is not affected by the layer. When the angle between the detonation direction of the strip-shaped charge and the layer is not 90° , the blasting stress wave will reflect and transmit at the layer, and the propagation process of the blasting stress wave will be extremely complicated. In this experimental design, the angle between the detonation direction of the slit charge and the layer is 90° ; that is,

the slit charge is perpendicular to the layer, which avoids the interference of the complex transmission and reflection behavior of the blasting stress wave at the layer on the analysis of the experimental results. Therefore, the pressure relief effect of the blasting gas at the layer will become the main factor affecting the blasting effect.

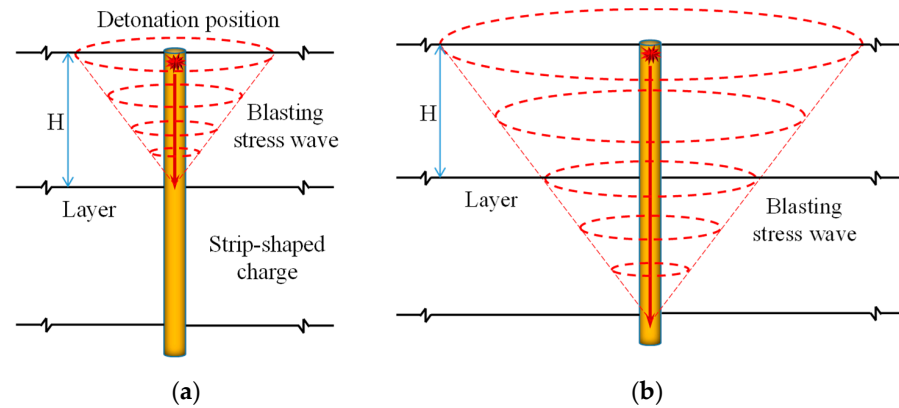


Figure 2. Detonation propagation and stress wave propagation process of strip-shaped charge in the layered rock mass: (a) $t = t_1$; (b) $t = t_1 + \Delta t$.

The dynamic fracture characteristics of polymethyl methacrylate (PMMA) and rock exhibit remarkable similarities [19,20]. In the model experiment, multi-layer PMMA plates are used as the layered rock mass specimen. A 5 mm circular diameter borehole is cut in the center of the specimen using a laser. The size of the PMMA plate is 300 mm $\times$ 300 mm $\times$ 4 mm, and fourteen PMMA plates of this size are stacked and fixed with clamps as a layered rock mass specimen. Lead azide is used as the model experimental explosive, and lead azide is put into a copper slit tube to make a slit charge. The length of the slit charge is 56 mm; the outer diameter is 5 mm, the inner diameter is 3 mm, and the slit width is 0.8 mm. In order to ensure the structural stability of the slit charge, the slit length is set to 48 mm, and 4 mm length is reserved on both sides of the slit tube without setting slits. The charge length is equivalent to the slit length; that is, the charge length is 48 mm, and the two ends of the slit tube are not charged.

A high-voltage probe is used to detonate the slit charge, and the detonation point is at the end of the charge. Figure 3 shows the blast-induced crack distribution of the layered rock mass specimen, and Figure 4 shows the slit tube after blasting. After blasting, long directional cracks are formed along the slit direction, and the copper slit tube is not obviously damaged, which provides an effective restraint for the directional release of blasting energy. To facilitate further analysis, the PMMA plates at different positions in the layered rock mass specimen are numbered as shown in Figure 4. The second to thirteenth layers are charging sections, and the second layer is the detonation position. The first layer and the fourteenth layer are non-charging sections, corresponding to the positions of both ends of the slit tube, and there are no slits in such positions.

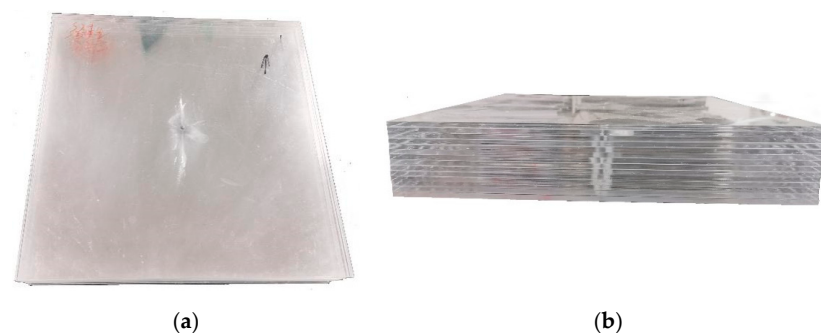


Figure 3. Blast-induced crack distribution of the layered rock mass specimen: (a) front view; (b) side view.



Figure 4. Slit tube after blasting and the corresponding layer number.

3. Fracture and Damage Analysis of Model Experiments

3.1. Directional Fracture Analysis

Binarization is performed on each layer of the PMMA plates of the layered rock mass specimen after blasting to obtain the crack distribution state of each layer of the specimen, as shown in Figure 5. It can be seen in the figure that most of the PMMA plates have formed long directional cracks along the slit direction, indicating that the slit charge can still exert a good directional fracture effect in the layered rock mass. There continue to be obvious differences in the failure morphology and crack distribution of different layers. The cracks at the end layers (the 12th and 13th layers) are short and randomly distributed, and the directional fracture effect is relatively poor. Although the PMMA plates on the first and fourteenth layers are not charged with explosives, they were still damaged under the blasting load of adjacent layers. In particular, the first layer forms long directional cracks along the slit direction.

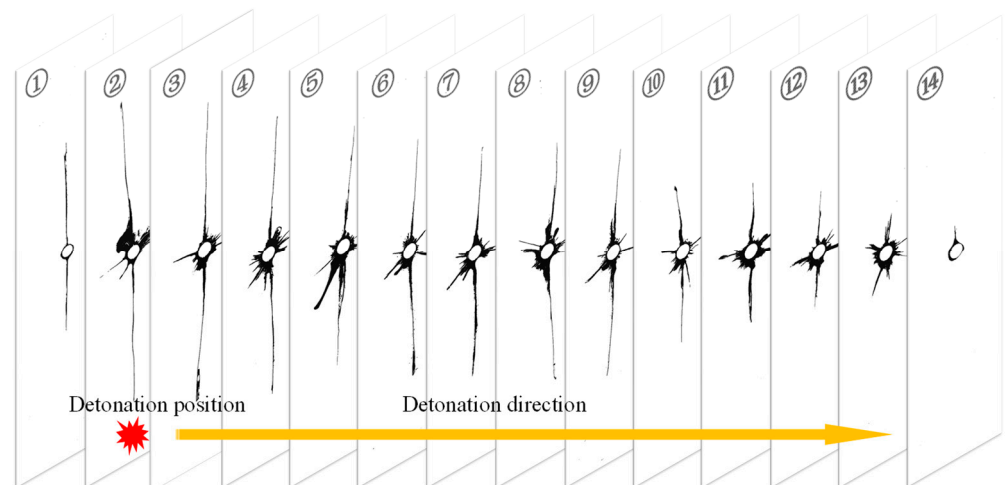


Figure 5. Crack distribution state of each layer of the specimen after blasting.

The propagation length of the directional crack is an important index used to evaluate the blasting effect of the slit charge. The lengths of the directional cracks in each layer in Figure 5 are measured, and the statistical data shown in Table 1 are obtained. There are also some differences in the propagation lengths of the two directional cracks at the same layer. Therefore, the average length of the two directional cracks is taken for further analysis.

Table 1. The lengths of the directional cracks in each layer of the specimen.

Layer Number	1st	2nd	3rd	4th	5th	6th	7th
Length 1/mm	37	57	51	47	40	38	35
Length 2/mm	27	53	52	49	39	44	42
Average length/mm	32	55	52	48	40	41	39
Layer number	8th	9th	10th	11th	12th	13th	14th
Length 1/mm	34	34	24	24	19	10	6
Length 2/mm	40	38	30	23	16	6	0
Average length/mm	37	36	27	24	18	8	3

Figure 6 shows the changing curve of the average length of directional cracks with the layer number (detonation direction) in the model experiment. The average length of the directional cracks in the second layer (initiation position) is the largest, which is 55 mm. Except for the first and fourteenth layers, the average length of the directional cracks gradually decreases along the detonation direction. In the unlayered rock mass, when the slit charge is detonated from one end, the previous research results show that the length of the directional crack increases first and then decreases along the detonation direction [21]. It can be seen that the changing law of the directional crack length along the detonation direction in the layered rock mass is significantly different from that in the unlayered rock mass. The distribution law of the directional crack length in the layered rock mass along the detonation direction shows that in engineering practice, the directional fracture effect of the layered rock mass can be improved by detonating both ends of the slit charge at the same time.

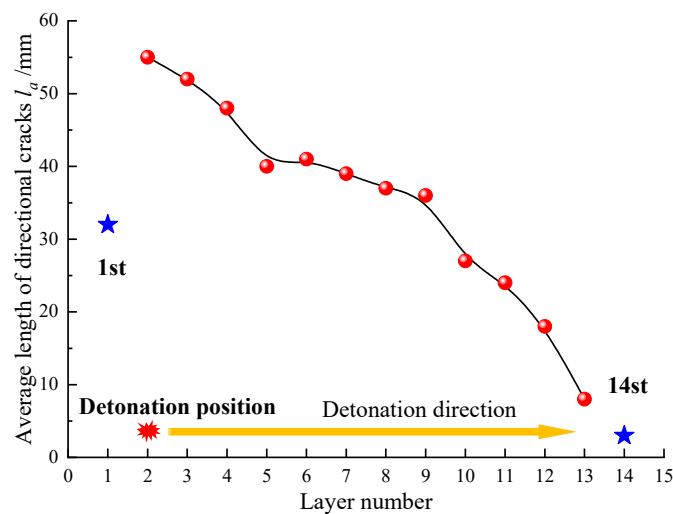


Figure 6. Changing curve of the average length of directional cracks with the layer number.

3.2. Damage Characteristic Analysis

Based on the binarized image of the blast-induced crack in the PMMA plate, the fractal dimension of the crack distribution of each layer is calculated using the box counting dimension method. According to the basic principle of the box counting dimension, the fractal dimension of any non-empty bounded target set can be expressed as follows [22]:

$$D = \lim_{k \rightarrow \infty} \frac{\lg N(\delta_k)}{-\lg \delta_k} \quad (1)$$

where D is the fractal dimension; δ_k is a decreasing sequence with the square grid side length as the element; and $N(\delta_k)$ is the minimum number of grids required to cover the target geometry with a square grid with a side length δ_k .

Figure 7 shows the fractal dimension calculation of the crack distribution of PMMA plates at partial layers. There are pronounced differences in the fractal dimension of cracks in different layers. In the quantitative analysis of rock blasting damage, the fractal dimension can be used to characterize the damage degree. The corresponding relationship between fractal damage ω and crack fractal dimension D under the blasting load can be expressed as follows [23]:

$$\omega = \frac{D - D_0}{D_{\max} - D_0} \quad (2)$$

where ω is the fractal damage under blast loading; D is the fractal dimension of blast-induced cracks after blasting; D_0 is the fractal dimension before blasting; and $D_{\max}$ is the

fractal dimension under complete damage and destruction. For two-dimensional plane problems, $D_{\max} = 2$; for three-dimensional problems, $D_{\max} = 3$.

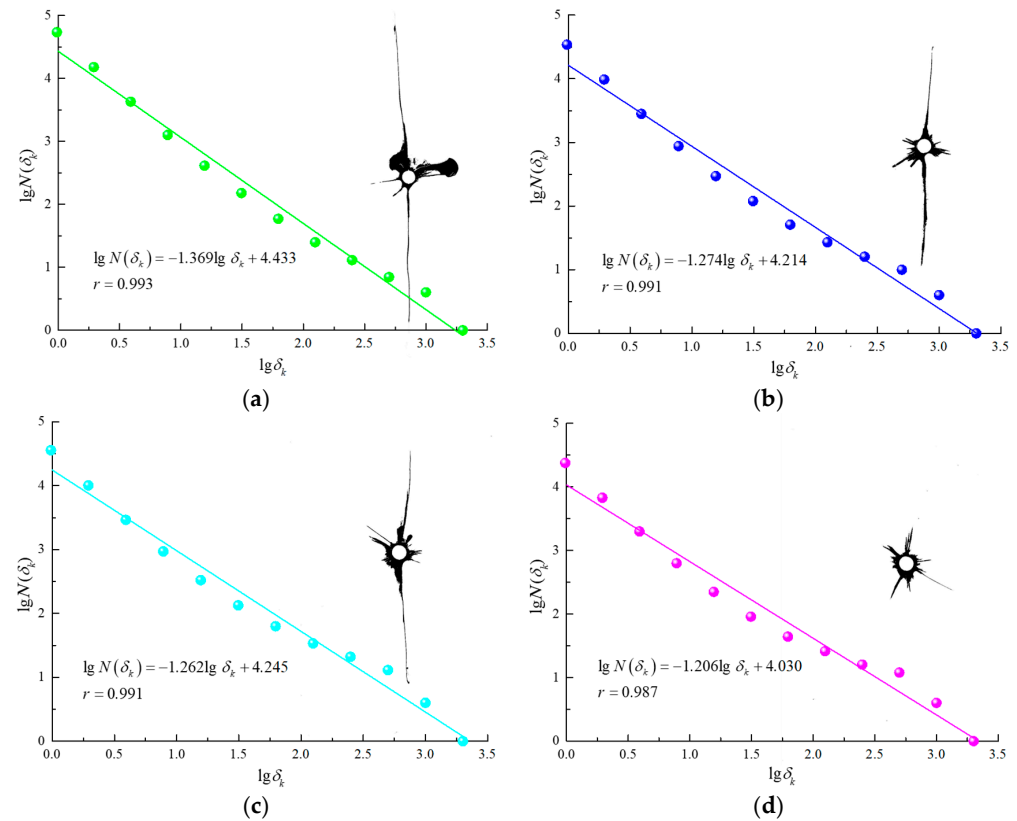


Figure 7. Fractal dimension calculation of the crack distribution of PMMA plates at partial layers: (a) second layer; (b) seventh layer; (c) eighth layer; (d) thirteenth layer.

It should be noted that for this model experiment, the PMMA plate is homogeneous and non-damaged before blasting, so $D_0 = 0$, $\omega = 0$. According to the above calculation results, the fractal dimension and the damage value of each layer of the specimen shown in Table 2 are obtained, and the changing curve of the damage value with the layer number shown in Figure 8 is further drawn. It can be observed in the figure that the damage values of the first and fourteenth layers (non-charging, no slit) are the smallest, and the damage value of the second layer (detonation position) is the largest. The damage value gradually decreases with the increase in the layer number. That is, in the layered rock mass, the blasting damage shows a gradually decreasing variation along the detonation direction. This is basically consistent with the distribution law of the directional crack propagation length along the detonation direction obtained by the previous analysis. The crack distribution and damage fracture in the layered rock mass are significantly different from that in the unlayered rock mass.

Table 2. Fractal dimension and damage value of each layer of the specimen.

Layer Number	1st	2nd	3rd	4th	5th	6th	7th
Fractal dimension	1.049	1.369	1.324	1.294	1.245	1.245	1.274
Damage value	0.525	0.685	0.662	0.647	0.623	0.623	0.637
Layer number	8th	9th	10th	11th	12th	13th	14th
Fractal dimension	1.262	1.225	1.252	1.251	1.193	1.206	1.012
Damage value	0.631	0.613	0.626	0.626	0.597	0.603	0.506

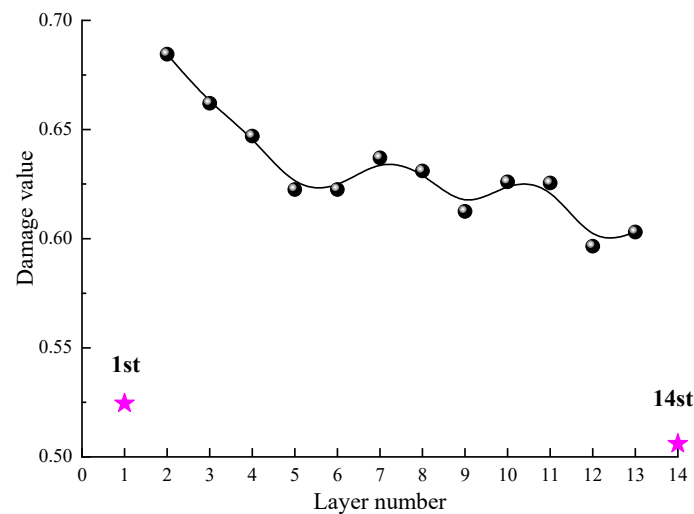


Figure 8. Changing curve of the damage value with the layer number.

4. Modeling and Parameters of Numerical Simulations

In order to obtain the damage distribution characteristics of slit charge blasting in the layered rock mass, numerical simulation analysis is carried out using the LS-DYNA program. LS-DYNA program is capable of solving a wide range of nonlinear problems, including material nonlinearity, geometric nonlinearity, and contact nonlinearity. This program is extensively utilized in the fields of high-speed impact, blasting engineering, seismic construction, and other related areas. The primary calculation methods employed by the LS-DYNA program include the Lagrange algorithm, the Euler algorithm, ALE (Arbitrary Lagrange–Euler) algorithm, and the Smoothed Particle Hydrodynamics (SPH) algorithm [24,25]. With reference to the relevant parameters of the model experiment, the numerical simulation model shown in Figure 9 is established. The numerical simulation adopts a quarter-symmetrical modeling method, which not only facilitates the comparative analysis of damage characteristics in different directions but also reduces the number of elements and increases the computational efficiency. The quarter model shown in Figure 9 is 150 cm in length and width and 56 cm in height. The model consists of 14 layers of rock mass, each with a thickness of 4 cm. In the numerical model, the diameter of the borehole is 5 cm, and the outer and inner diameters of the slit charge are 5 cm and 3 cm, respectively. Similar to the model experiment, the positions of the slit charge corresponding to the first layer and the fourteenth layer of rock mass are not charged, the explosive is detonated from the second layer of the rock mass and propagated to the direction of the fourteenth layer of the rock mass.

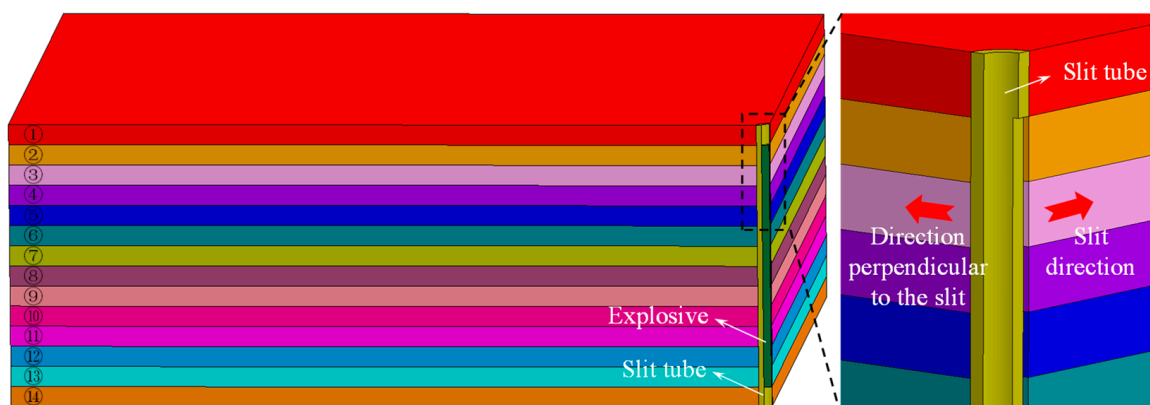


Figure 9. Schematic diagram of numerical simulation modeling.

In the numerical simulation, the constitutive model of the rock mass is the RHT model, which is a constitutive model that can characterize the damage characteristics of rock materials under impact and blast loads. The constitutive model introduces the influence of the third invariant J_3 of the deviatoric stress tensor on the shape of the failure surface, and J_3 can qualitatively determine the strain type and stress state of the material. Furthermore, the strength of the rock material increases under dynamic loading due to the strain rate effect. The RHT model describes the strain rate effects of materials under compression and tension by introducing a dynamic strain rate enhancement factor. The damage variable D in this model is the ratio of the cumulative equivalent plastic strain increment to the final failure equivalent plastic strain. The main parameters of the rock material in the numerical simulation are shown in Table 3.

Table 3. Main parameters of the rock material.

Mass Density RO (kg/m ³)	Initial Porosity ALPHA	Crush Pressure PEL (MPa)	Compaction Pressure PCO (GPa)	Elastic Shear Modulus SHEAR (GPa)	Compressive Strength FC (MPa)
2700	1.1	40	6.0	24.17	119

In the numerical simulation, the high-energy explosive model is used for the explosive, and the JWL equation is introduced to describe the relationship between pressure and volume during the blasting process. The main parameters of the explosive material in the numerical simulation are shown in Table 4.

Table 4. Main parameters of the explosive.

Mass Density RO (kN/m ³)	Detonation Velocity D (m/s)	Detonation Pressure PCJ (GPa)
11.8	3800	5.53

In order to simplify the calculation, the contact property of the layered rock mass is defined as automatic surface–surface contact, and the fluid–structure coupling algorithm is used between the explosive and the rock mass. Under the action of the blasting load, the rock mass element around the borehole will be greatly deformed, which affects the convergence of numerical simulation calculation. Therefore, by introducing the *MAT_ADD_EROSION command to control the failure of the rock mass element with large deformations, the failure strain of the rock mass element is set to 0.2.

5. Damage Distribution Characteristics of Numerical Simulations

Figure 10 shows the overall damage distribution cloud map from the second layer to the thirteenth layer. It can be seen in the figure that for the overall model, the damage degree and damage range in the slit direction are significantly larger than those perpendicular to the slit direction. In addition, it is found that the damage degree and damage range in the slit direction gradually decrease along the detonation direction, which is basically consistent with the analysis results of the model experiment. The damage distribution of the layered rock mass is obviously discontinuous, which is significantly different from that of the unlayered rock mass.

Figure 11 shows the damage distribution of each layer of the layered rock mass model after blasting. It can be seen in the figure that the damage degree in the slit direction is significantly greater than that in other directions. The slit charge can increase the damage in the slit direction and reduce the damage in the non-slit direction so as to achieve directional fracture and protect the surrounding rock. In addition, the discontinuous nature of the layered rock mass also leads to differences in damage distribution in different layers. The

damage change characteristics of each layer in the slit direction are consistent with the previous experimental analysis results.

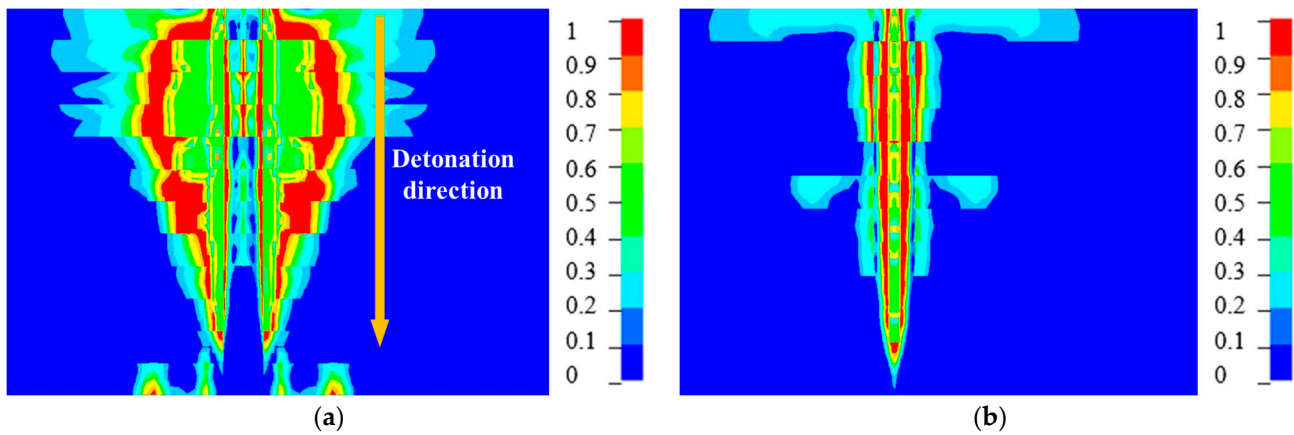


Figure 10. Overall damage distribution of the layered rock mass model after blasting: (a) slit direction; (b) perpendicular to the slit direction.

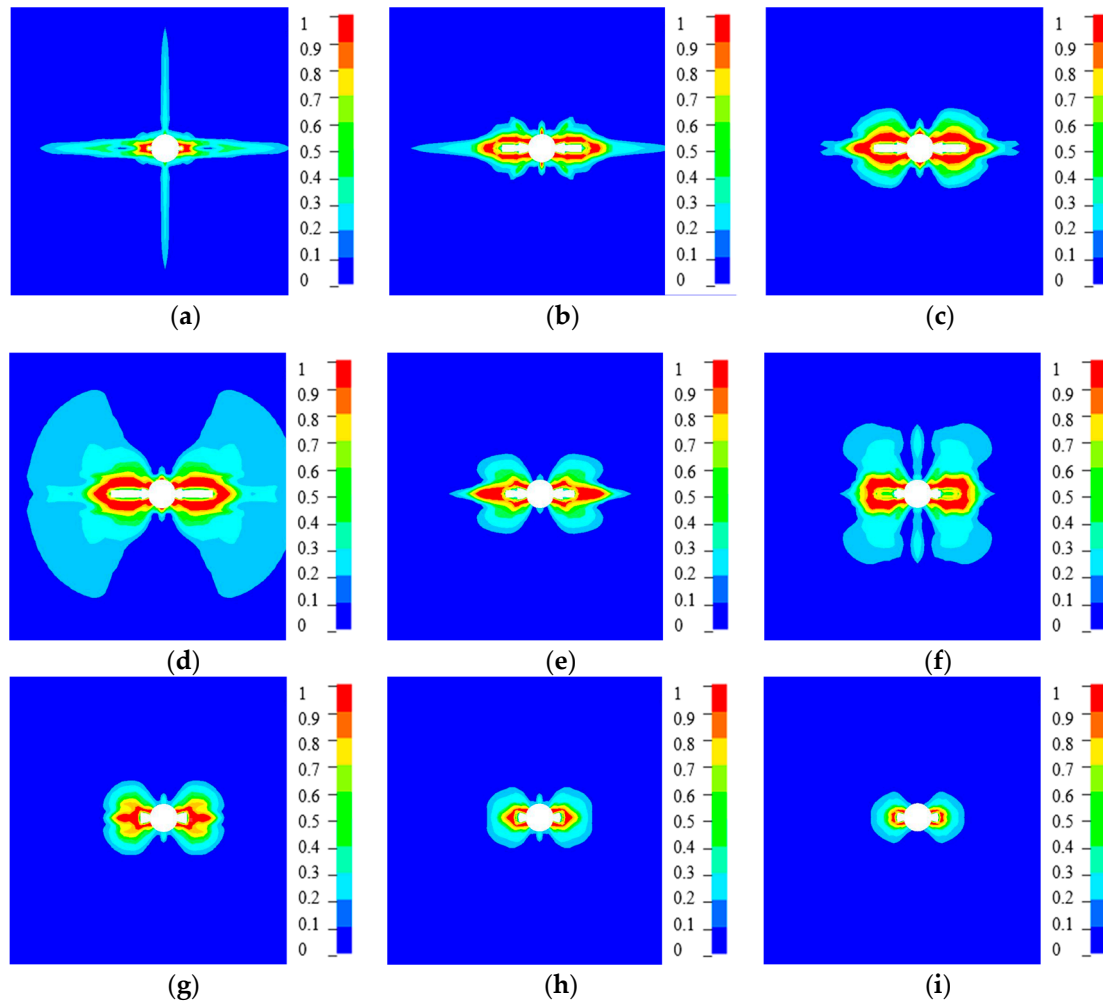


Figure 11. Damage distribution of each layer of the layered rock mass model after blasting: (a) second layer; (b) third layer; (c) fourth layer; (d) fifth layer; (e) sixth layer; (f) seventh layer; (g) eighth layer; (h) ninth layer; (i) tenth layer.

6. Conclusions

The pressure relief of blasting gas at the layer is the main factor affecting the blasting effect of the layered rock mass. The model experiment results show that the directional crack length in the slit direction is significantly larger than that in other directions when slit charge blasting is carried out in the layered rock mass. This shows that the slit charge can still play a good directional fracture effect in the blasting of the layered rock mass. However, unlike blasting in the unlayered rock mass, when blasting in the layered rock mass, the directional crack length gradually decreases along the detonation direction. Based on the fractal damage theory, the damage value of each layer of rock mass in the model experiment is calculated and analyzed, and it is found that the damage value of a single layer of rock mass also shows a trend of decreasing along the detonation direction. Furthermore, the numerical simulation analysis results show that the damage distribution of the layered rock mass presents obvious discontinuous characteristics, and the damage in the slit direction gradually decreases along the detonation direction, which is significantly different from the damage characteristics of the unlayered rock mass. The analysis results of the model experiment and numerical simulation are consistent.

In engineering practice, according to the changing law of directional crack length and damage distribution in the layered rock mass along the detonation direction, the directional fracture effect of the layered rock mass can be improved by detonating both ends of the slit charge at the same time.

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