Numerical Simulation of Parallel Cutting with Different Number of Empty Holes

Xiantang ZHANG*, Juan LI, Dan LI, Shizhen XIE, Hongmin ZHOU, Tingchun LI

Abstract: The cutting blasting plays a key role in rock excavation construction, which determines the blasting effect and efficiency of the entire blasting project. In the cutting blasting, parallel holes are often used as the auxiliary free surface and the compensation space of blasting rock, and the empty holes have a great influence on the blasting effect. In this paper, Ansys/Ls-Dyna finite element analysis software is carried out to simulate four models with different number of empty holes. The simulation results show that the stronger the guiding effect of the empty holes on the crack propagation, the more obvious the inhibition effect on the crack in the remaining direction. The initial crack near the empty hole is generated by the continuous action of the stress wave, and the empty hole promotes the propagation of the explosion stress wave. The inconsistent guiding directions of adjacent empty holes are one of the reasons for the unsatisfactory blasting effect of multiple small diameter empty holes. The closer the empty hole is to the blasthole, the larger the maximum principal stress. By comparing the results of calculation with the numerical simulation, it is verified that the maximum principal stress near the empty hole is similar and the change rule is consistent. The above research has reference meaning to the location of the hollow hole in the actual blasting construction and the density of the empty hole.

Keywords: action mechanism of empty hole; numerical simulation; parallel cut; rock fragmentation process; stress concentration

1 INTRODUCTION

The empty hole can provide auxiliary free surface and the compensation space of rock breaking process for blasting. Theoretically, it is possible to increase the blasting effect by appropriately increasing the volume of empty holes, but the diameter of the empty hole and the diameter of the blasthole are the same in some conditions under the actual blasting construction. In this case, there may be multiple small diameter blastholes due to the equipment error and the quality of the operator will cause the blasting effect to be unsatisfactory or even fail. This paper explores the reason for the other side, the influence of the guiding effect of adjacent holes on the blasting effect when the multi-holes are arranged.

Numerical simulation makes up for the limitation of the field test and the complexity of theoretical calculation, and it becomes a new method to study rock blasting failure mechanism and predicting blasting result. Li Qiyue [1] established a theoretical model by ANSYS finite element analysis software, and obtained that the tensile failure and compression damage of rock under stress wave are more obvious with the increase of empty hole diameter. In Zhang Qi [2] by means of mechanical model and numerical calculation, the factors influencing the effect of cutting blasting are quantitatively analyzed, as well as the effect of empty holes in Parallel cutting. Lin Daneng [3] based on the typical blasthole layout with empty holes, theoretically obtained the stress concentration effect, and the stress concentration effect will increase with the increase of the aperture. Ren Xing [4] from the point of numerical simulation concluded that the stress wave will decay gradually with the increase of distance in the propagation process. Zhu Zheming [5] established the fracture failure criterion of brittle materials under compressive loading based on the collinear double crack model and the single crack model and the traditional crack fracture criterion. Yang Renshu [6] studied the variation of the crack propagation trajectory, the expansion velocity and the dynamic stress intensity factor of the crack tip under different empty holes diameters. In Zhu Z [7] by using linear equation of state and the major principal stress failure criterion, numerical models were established by using AUTODYN code, and the effective mechanism of empty holes on crack propagation behavior was studied numerically. The results show the following: Empty holes have the arrest function on outgoing cracks, and the arrest function depends on the two holes spacing; the shorter the two holes spacing is, the stronger the arrest function is. Wang Y. [8] - combining the experimental and numerical results, it can be concluded that the influence of empty hole defects of brittle materials on dynamic fracturing is great. Yan Yaofeng [9] used numerical simulation to observe the stress cloud diagram and stress time history curve during the explosion process, and obtained the effect of empty holes effect on rock failure under the condition of empty holes.

There are many researches on the influence of the diameter of the empty hole on the blasting effect, and the research on the influence of the number of empty holes and the position of the empty hole on the blasting rock breaking effect is less.

2 GEOMETRIC MODEL AND STATE PARAMETERS
2.1 Establishment of Geometric Models

Design excavation section 12 m^2 in a mining area in northern China, no inclination angle. Rock firmness coefficient f = 15. The nature of the rock is solid granite. The density is 2.471 g/cm^3. The compressive strength of rock is 150MPa, Poisson's ratio is 0.25. The rock formation is stable and does not contain water, and has a simple geological structure. According to the field blasting experiment, the cutting model was established as four blast holes, which includes four models: Model I, four blast holes plus center empty hole diamond arrangement; Model II, four blast holes and two vertical empty holes in a diamond arrangement; Model III, four blast holes and three vertical empty holes in a diamond arrangement; Model IV, four blast holes and four vertical empty holes in a diamond arrangement.

The overall model size is 600 × 600 × 1 cm, the blast hole diameter is 0.04 m, A, B, C, D blast holes are charging holes, E, F, G, H are empty holes, and the specific spacing and blast holes arrangement are shown in Fig. 1. (Unit: mm).
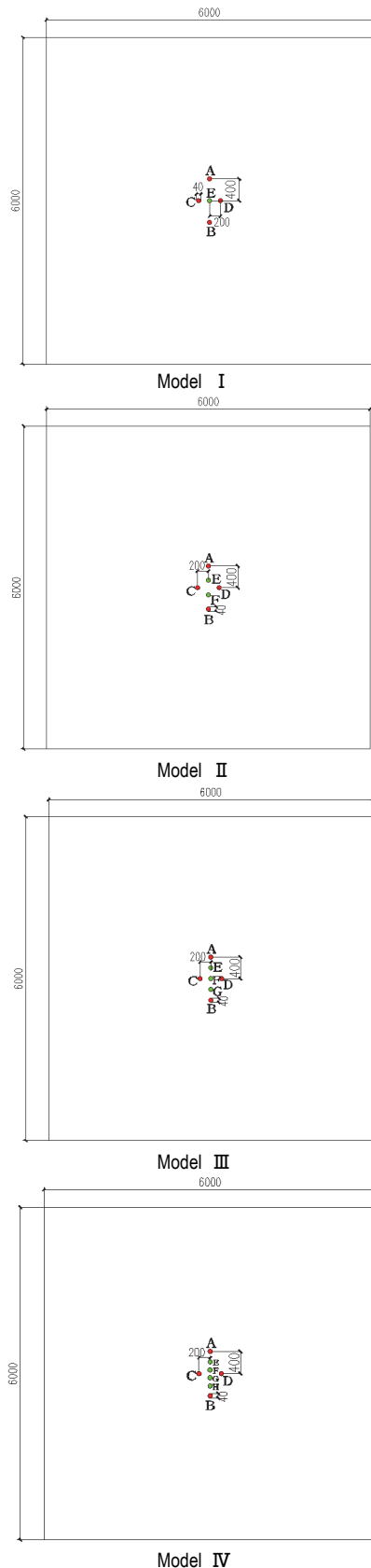
Model Ⅰ

Model Ⅱ

Model Ⅲ

Model Ⅳ

Figure 1 Specific spacing and blast holes arrangement

2.2 Material Parameters
2.2.1 Unit Algorithm

Model uses SOLID164 hexahedral solid element, coupled with charges; In order to prevent the reflection superposition of the explosive stress wave from affecting

the calculation result, no reflection boundary condition is set around the model; Apply fixed constraints to the bottom of the model to prevent rigid body displacement; Simulation is simplified to a plane strain problem, calculated using a single layer grid; when calculating, all holes detonate at the same time. A Fluid-structure interaction algorithm is selected for the calculation model.

2.2.2 Rock Model

The constitutive model of rock media uses HJC constitutive equation to simulate the large deformation behavior and high strain rate characteristics of rock under explosion impact dynamic load, and the key word is *MAT_JOHNSON_HOLMQUIST_CONCRETE.

By adding the failure criterion, the damage and failure of the unit are used to simulate the dynamic expansion of the rock crack and the formation process of the cavity. The specific rock material parameters are shown in Tab. 1 [10].

Table 1 Material parameters of HJC model of rock material

Density ρ / g/cm^3	2.471	Pressure parameter K_1 / GPa	85
Compressive strength f_c / MPa	150	Pressure parameter K_2 / GPa	171
Shear modulus G / GPa	29.2	Pressure parameter K_3 / GPa	208
Tensile strength T / MPa	6	P_1 / GPa	1.00
Crush volume pressure P_C / MPa	51	Compacted volume pressure U_1	0.01
Crush volume strain U_C	0.00278	Compacted volume strain A	0.79
Poisson's ratio	0.3	Cohesion strength B	1.60
Maximum standard strength SF_{max}	4	Strength parameter N	0.61
Minimum plastic strain change EF_{min}	0.005	Failure type f_s	0.004

2.2.3 Explosive Model

The calculation model of explosive material is MAT_HIGH_EXPLOSIVE_BURN, and the EOS_JWL state equation is used to reflect the change of volume and pressure of detonation results after explosion, The JWL state equation is shown in Eq. (1):

$$p = A\left(1-\frac{\omega}{R_1}\right)e^{-R_1V} + B\left(1-\frac{\omega}{R_2V}\right)e^{-R_2V} + \frac{\omega E_0}{V} \quad (1)$$

where, p is the pressure of the detonation product; V is the relative volume of the detonation product; E_0 is the initial internal energy density of the detonation product; A, B, R_1, R_2, ω are material parameters.

Table 2 No. 11th rock explosive parameters

Density	kg/m^3	1200
Explosion velocity	GPa	4950
CJ pressure	GPa	6.125
Parameter of JWL state equation	A / GPa	52.4
	B / GPa	0.768
	R_1	4.2
	R_2	1.1
	ω	0.34
	E / GPa	8.5

In this paper, the number 11th rock explosive is selected, and its parameters are shown in Tab. 2 [11-13].

Table 3 Parameters of air material parameters and State equations

Density / g/cm³	1.29E−5
C_0	0
C_1	0
C_2	0
C_3	0
C_4	0.4
C_5	0.4
C_6	0
E / GPa	0.025

2.2.4 Air Model

The air material model chooses the MAT_NULL air material model, its state equation is defined by the keyword EOS_LINERAR_POLYNOMIAL, and state equation is shown in Eq. (2):

$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + \left(C_4 + C_5\mu + C_6\mu^2\right)E \qquad (2)$$

where, C_i is the equation parameter, E is the unit initial internal energy of relative volume, $\mu = 1/(v - 1)$, V is relative volume [14-16].

Specific air parameters are shown in Tab. 3.

3 SIMULATION RESULTS ANALYSIS
3.1 Blasting Rock Breaking Process

The mass of the remaining rock in the cavity is an important index to reflect the cutting effect at the end of the cutting blasting. The cutting is designed to provide compensating space and the free surface for rock fragmentation. At the end of the cutting blasting, the less large masses of rock in the cavity, the more obvious the effect of the cutting.

The blasting penetration process of a rock model containing different number of holes is shown in Fig. 2 [17, 18].
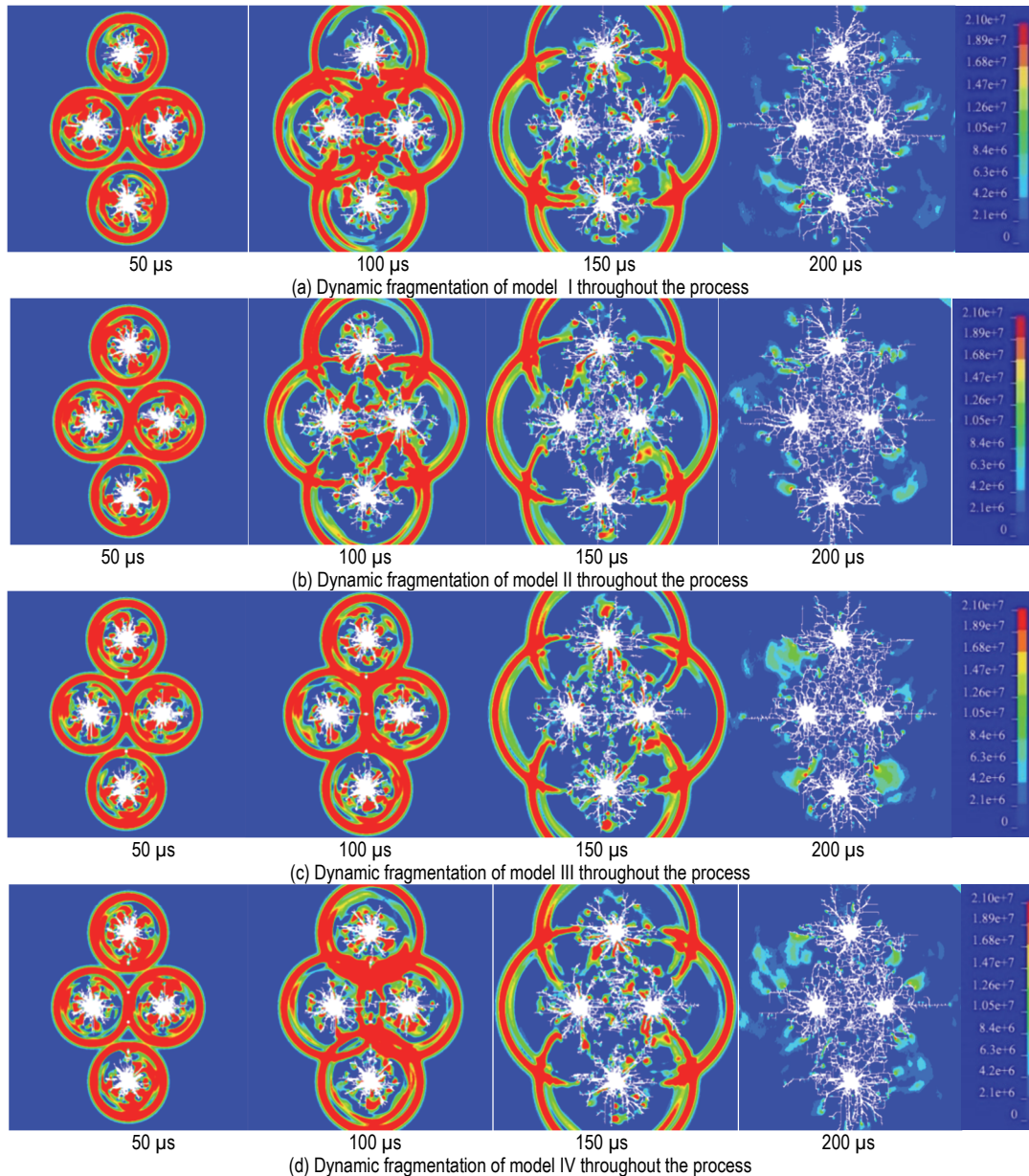

50 μs   100 μs   150 μs   200 μs
(a) Dynamic fragmentation of model I throughout the process

50 μs   100 μs   150 μs   200 μs
(b) Dynamic fragmentation of model II throughout the process

50 μs   100 μs   150 μs   200 μs
(c) Dynamic fragmentation of model III throughout the process

50 μs   100 μs   150 μs   200 μs
(d) Dynamic fragmentation of model IV throughout the process
Figure 2 Simulation diagram of dynamic rock breaking process of each model

The simulation results show that the blasthole detonation is within 80 μs, and the explosion stress wave propagates in all directions in the form of columnar waves. The rock around the blasthole has compressive damage uniformly distributed in all directions, the stress wave does not reach the empty hole, and the empty holes effect does not appear. At about 90 μs, the explosion stress waves reach the center of the model and begin to stack at this time. When the stress wave reaches the central empty hole of the model I and the Model III, it can be seen from the stress cloud diagram that the stress wave generates a reflection tensile stress at the central hole of the Model I and the Model III, and a stress concentration phenomenon occurs; At about 136 μs, the Model I and the Model III center empty hole cause the tensile damage to produce the crack, the crack along the horizontal direction expands. In addition, the empty holes E and holes G in the Model III due to the proximity of the blasthole, the empty hole guiding effect is obvious. The cracks mainly develop in the direction connecting the blasthole and the empty hole. The cracks of the empty hole E and G develop vertically, and that is inconsistent with the crack development direction of the center empty hole F, so that the cracks develop slowly when they extend to the central hole F.

This phenomenon is more evident in the Model IV. The empty hole E and the empty hole H in the Model IV are close to the blasthole A and the blasthole D respectively, at about 110 μs, because the stress wave arrives at the empty hole E and the empty hole H, and produces the horizontal direction tensile stress near the empty holes, therefore, the vertical crack expansion of the empty holes appeared, and penetrated in the main at 178 μs. This phenomenon effectively suppresses the crack propagation on the left and right sides of the two empty holes. The stress wave of the blasthole B and the blasthole C is superimposed at the empty hole F and the empty hole G at about 118 μs, and the vertical tensile stress is produced near the hole, which causes the horizontal crack to occur in the two holes at about 149 μs; the maximum principal stress direction of the empty hole E and empty hole F is different under the action of the explosive stress wave, because of the tensile stress of the hole E is in the horizontal direction, and the tensile stress of the empty hole F is in the vertical direction, the two empty holes are different in the direction of the crack orientation, so that the empty hole is connected in a large amount of rock.

Since the two empty holes in the Model II are far away from the blasthole, stress concentration occurs near the two empty holes at about 162 μs, and the tensile stress caused by the stress wave is pulled, and the crack propagation direction is approximately 45° with the horizontal direction. The guiding effect is not obvious, resulting in a larger amount of rock that has not been exploded, which is worse than other models.

3.2 Analysis of Numerical Simulation Results

Since each grid volume is divided into 1 cm³ when meshing, the volume of unexploded rock mass in the explosion chamber after the end of the simulation can be roughly judged according to the number of statistically non-failed cells [19]. The volume statistics of the remaining large block rocks in the cutting cavity is shown in Tab. 4.

Table 4 Remaining maximum block volume table of rock mass

Maximum block mass of remaining rock mass / cm³			
Model I	Model II	Model III	Model IV
100	400	350	380

After comparing the dynamic rock breaking process of four models, it is found that the model simulates the final cavity Volume: Model I > Model II > Model III > Model IV.

It can be seen from the simulation results that with the increase of the number of empty holes, the guide direction of the empty holes becomes inconsistent: In the Model III, the tensile stress in the middle empty hole is in the vertical direction, the crack is mainly horizontal, but the reflection tensile stress of the remaining two empty holes is in the horizontal direction, the crack along the vertical, leading to the formation of the cutting cavity inhibition, the remaining large size rock mass began to increase. In the Model IV, because the crack propagation direction of the empty hole E and the empty hole F is inconsistent, the rock block with the final cavity opening is the largest, the quantity is large, the cutting cavity is small, and the blasting effect is unsatisfactory. In the Model II, in addition to the large size and the number of larger, the guiding effect is not obvious, and the simulation results show that there are non-penetrating surfaces. The volume of the cutting cavity is smaller than the Model I.

The stress state of rock in the process of explosive loading is an important part of analyzing the law and characteristics of rock breaking, and the action process of explosive load to rock mass can be analyzed comprehensively by analyzing the stress characteristics of rocks at different positions. Take a unit at a distance of 200 mm from each blasthole to check the detonation pressure at that place. The location and unit number of each model are the same. The specific settings are shown in Fig. 3.
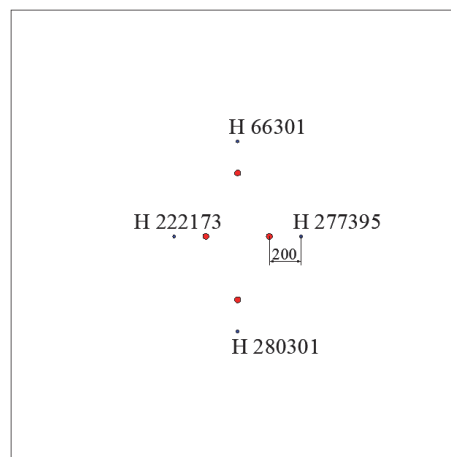

**Figure 3** Unit selection location and its number

The detonation pressure of the selected unit is shown in Fig. 4.

When the stress wave reaches the empty hole, the radial wave is generated near the wall of the hole under the action of the stress wave and the air in the hole, and then the rock near the empty hole is continuously destroyed under the "gas blade action" of the air. The presence of empty holes slow the decay of stress waves in the rock, so that as the number of empty holes increases and the distance between the empty holes and the blastholes
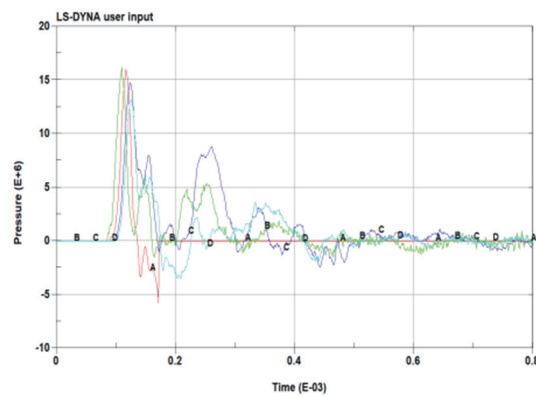
decreases, the peak of the detonation pressure gradually increases, which promotes the propagation of stress waves. However, due to the attenuation of the stress wave, the effect of the empty hole on the propagation of the stress wave will reach a peak and then gradually decrease.
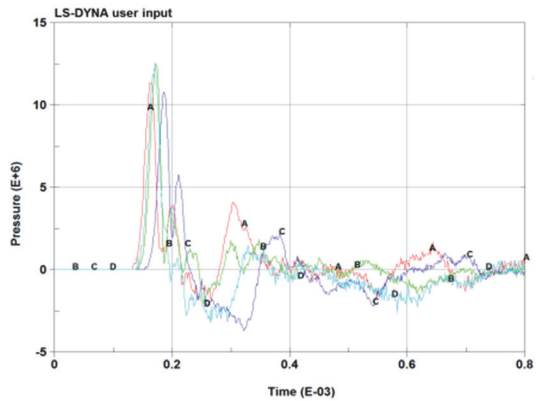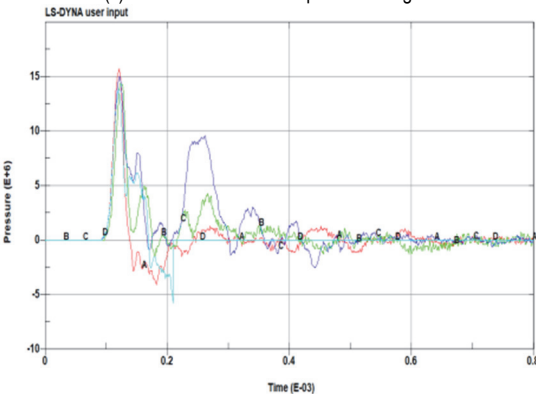

(a) Model Ⅰ detonation pressure diagram
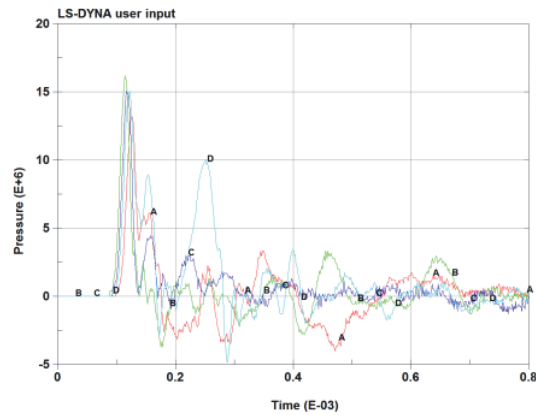
(b) Model Ⅱ detonation pressure diagram

(c) Model Ⅲ detonation pressure diagram

(d) Model Ⅳ detonation pressure diagram
Figure 4 Detonation pressure diagram of selected unit of each model

Combined with the simulation of the dynamic rock breaking process of each model in Fig. 2, it can be seen that as the number of holes increases and the distance between the empty holes and the blastholes decreases, the guiding effect of the empty holes on the cracks becomes less obvious, and the suppression of crack propagation in the remaining directions is gradually weakened. The crack on the outside of the blastholes becomes denser and more random as the distance between the empty hole and the blastholes increases.

4 THEORETICAL VERIFICATION OF THE EFFECT OF EXPLOSION STRESS WAVE ON EMPTY HOLE

The stress state near the empty hole is very different from that without it, and the stress concentration near the empty hole has a great influence on the guide direction of the empty hole. Each model bore a coupling charge, and at the same time, the detonation of the blast wave quickly decays to the stress wave, the peak attenuation law of the stress wave is shown in Eq. (3) [19, 20].

$$
\begin{cases}
\sigma_r = p_0 \left(\dfrac{r}{r_0} \right)^{-\alpha} \\
\sigma_\theta = -\lambda_{\mathrm{d}} \sigma_r
\end{cases}
\tag{3}
$$

where, σ_r is an additional radial stress in the explosion of a point in the rock, MPa; σ_θ is the tangential stress of an explosion at a point in the rock, MPa; p_0 is the initial pressure applied to the hole wall after the explosive explosion, MPa; γ_0 is the hole radius, m; γ is the distance from the center of the cannon Hole in the rock, m; α is the stress wave attenuation factor, and its relation is $2 - \mu_{\mathrm{d}}/(1 - \mu_{\mathrm{d}})$; μ_{d} is the dynamic Poisson ratio, and the relationship to the static Poisson ratio is $\mu_{\mathrm{d}} = 0.8\mu$; λ_{d} is the dynamic side stress coefficient, and its relation is $\lambda_{\mathrm{d}} = \mu_{\mathrm{d}}/(1 - \mu_{\mathrm{d}})$.

When the stress wave reaches the empty hole, the reflective tensile action at the wall of the holes will cause the stress concentration phenomenon near the empty hole. At this time, the stress peaks near the empty holes are shown by the theoretical Mechanics Eq. (4) [21-24]:

$$
\begin{cases}
\sigma_{rr} = \dfrac{1}{2} \begin{bmatrix} (1-k^2)(\sigma_\theta - \sigma_r) + \\ +(1-4k^2+3k^2)(\sigma_\theta\cos2\theta + \sigma_r\cos2\theta) \end{bmatrix} \\[3ex]
\sigma_{\theta\theta} = \dfrac{1}{2} \begin{bmatrix} (1+k^2)(\sigma_\theta - \sigma_r) + \\ +(1+3k^2)(\sigma_\theta\cos2\theta + \sigma_r\cos2\theta) \end{bmatrix} \\[3ex]
\tau_{r\theta} = \dfrac{1}{2} \left[(1+2k^2-3k^2)(\sigma_\theta\cos2\theta + \sigma_r\cos2\theta) \right] \\[2ex]
k = \dfrac{r_2}{r_{\mathrm{B}}}
\end{cases}
\tag{4}
$$

where, σ_{rr} is the radial stress under the effect of the empty holes, MPa; $\sigma_{\theta\theta}$ is the tangential stress under the void hole effect, MPa; $\tau_{r\theta}$ is the shear stress under void hole effect, MPa; r_2 is the empty hole radius, m; θ is the angle between the calculation point and the center line of the cannon Hole and the line of the empty hole center. r_{B} is the distance from

the point to the center of the empty hole, *m*.

By analyzing the above two formulas, they can calculate the stress peaks near the hole wall and the hole wall, however the stress peak calculation of the other points in the cutting cavity after the stress wave superposition has problems, but the numerical simulation can get the stress state of any point.

Substituting the parameters into the formula, $r_2 = r_B$, $k = 1$:

$\sigma_{rr} = 0$; $\tau_{\gamma\theta} = 0$; $\sigma_{\theta\theta} = \sigma_\theta(1 + 2cos\theta) + \sigma_r(2cos\theta - 1)$, when $\theta = \pm\pi$, the maximum principal stress size near an empty hole is: $\sigma_{\theta\theta max} = 3\sigma_\theta + \sigma_r = p_0(r/r_0)^{\wedge}(-\alpha) - 3\lambda_d\sigma_r$.

The calculation results of the maximum principal stress at each hole wall are compared with the simulation results as shown in Tab. 5. After comparison, the calculation results are numerically different from the simulated values, but the sizes are not much different, and the variation law is consistent.

Table 5 Calculated results and simulation results of maximum principal stress at each empty hole wall (MPa)

Model number	Empty hole number	E	F	G	H
Model I	Calculated values	135			
	Simulation results	127			
Model II	Calculated values	74	64		
	Simulation results	68	57		
Model III	Calculated values	78	118	62	
	Simulation results	71	110	57	
Model IV	Calculated values	91	100	97	72
	Simulation results	79	89	86	66

5 CONCLUSIONS

The finite element software is used to simulate the crack penetration process of a different number of empty holes and the break-through process of the cutting cavity, and the following conclusions are obtained by the numerical simulation and the theoretical analysis of the effect of the stress wave on the empty hole, and the conclusions are as follows:

(1) The guide direction of the empty hole is the maximum principal stress direction; the crack around the empty hole is caused by the continuous action of the stress wave; due to the stress concentration phenomenon of the empty hole, the crack mainly develops to the empty hole connection direction, and the other direction crack propagation is suppressed. The guiding action of the empty hole is more obvious, the stronger the suppression of crack propagation in other directions, the cavity volume will be reduced correspondingly. At the same time, the empty hole promoted the propagation of the explosion stress wave, and this promotion is gradually weakened due to the attenuation of the stress wave.

(2) When the multi-empty hole is arranged, the inconsistent orientation direction of the adjacent empty holes will lead to less crack through the empty holes or even wear, so that the blasting effect is not ideal or even the blasting failure. In the actual blasting construction, the arrangement position of the empty holes and the density of the empty holes should be considered, and whether the guiding direction of the adjacent empty holes is conducive to the formation of the cavity.

(3) The theoretical calculation and numerical simulation results of the effect of the explosion stress wave on the cavity show the following: the existence of the empty hole changes the stress distribution around the empty hole and produces the stress concentration phenomenon. By comparing the stress simulation results and the calculation results around the holes, the closer the empty holes are to the blasthole, the larger the maximum principal stress. It shows that in the process of stress wave propagation, as the stress wave propagates outward, the

attenuation trend appears. The maximum principal stress of the empty hole is similar to the symmetrical arrangement, the simulation result is similar to the calculated result, and the change law is consistent.

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