

## Research Article

# Influence of Charge Hole Spacing on the Crack Propagation Behavior under the Effect of Empty-Hole Directional Blasting

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In order to explore the reasonable spacing of charge holes in empty-hole directional blasting, based on the action mechanism of empty-hole directional blasting, the influence of charge hole spacing on crack propagation is studied, the calculation formula of charge hole spacing is deduced, and the blasting excavation process in Shijiazhuang South Ring Expressway Tunnel is simulated by finite element software. The results show that by setting empty holes on both sides of the charge holes in the peripheral blasting, the guiding cracks can be formed in the connecting direction between the empty hole and the charge hole, the propagation of cracks in other directions can be suppressed, and the spacing of charge holes can be enlarged. Reasonable charge hole spacing is very important to realize the effect of empty-hole directional blasting; the spacing is small, the rock will be overbroken, and the utilization ratio of explosives is reduced; large spacing, the guiding effect of empty holes is weak, and the effective directional cracks cannot be formed. The spacing between charge holes is closely related to the mechanical properties of rock, detonation parameters of explosive, and aperture of the charge hole and empty hole. According to the simulation results of crack propagation in different spacing, the blasting performance is the best when the charge hole spacing is 800–1000 mm, which is completely consistent with the theoretical calculation result of charge hole spacing 948 mm.

## 1. Introduction

Ordinary peripheral blasting can form cracks between the blastholes, but a large number of random cracks will also be generated in other directions around the holes, leading to the decrease of the stability and integrity of surrounding rock [1]. In order to meet the excavation requirements of blasting and to protect the stability of surrounding rock, directional fracture controlled blasting technology has been proposed [2]. Among them, empty-hole directional blasting can make rock blasting within a certain distance form stress concentration around the empty hole [3], guide the priority propagation of initiation crack toward the direction of the empty hole, improve the blasting performance of roadway excavation, and realize the purpose of directional blasting.

As for the research of the empty hole in blasting engineering, Mohanty [4, 5] proposed and verified by experiments that the radial controlled cracks can be produced by setting the empty hole on both sides of the charge hole, and

the directional blasting effect equivalent to that of notched blasting is obtained. In recent years, more and more scholars have conducted a multiangle research on empty-hole directional controlled blasting in combination with mechanics theory, field experiments, and numerical simulation calculation.

Based on the elastodynamics, Zhou et al. [6] investigated the scattering of elastic waves and dynamic stress concentrations in infinite exponential graded materials with two elliptic holes and found that the mutual effect between two holes makes the dynamic stress of top half greater than bottom half. According to the theory of elastic mechanics, Liu et al. [7] studied the mechanism of the empty hole effect in cut blasting and concluded that the effect of stress concentration will be produced by the empty hole. Li et al. [8] deduced the formula concerning on the empty hole effect under blasting stress by using elastic mechanics theory and improved and verified the calculation model of the empty hole effect. Malezhik et al. [9] analyzed the crack evolution

between holes and dynamic-stress intensity factors surrounding the crack tip and revealed the effects of empty hole spacing and shape on the propagation cracks.

The empty holes can improve the distribution of tensile stress in surrounding rock and guide the initiation and propagation of cracks [10]. The different cracking patterns under the configurations with and without guide holes and a notched guide hole between two charging boreholes were examined [11–15]. The dynamic caustic experiment method is used to study the effects of empty hole diameters on crack propagation, and in a certain range, the larger the hole diameter is, the more obvious the guiding effect of the empty holes is on the blasting cracks [1, 16–18]. Uysal [19] found that the empty barrier holes can effectively reduce the seismic vibration by a series of field experiments in a dragline panel. Wang [20] analyzed the propagation speed and stress intensity factor of the main crack tips in five cases and compared the average propagation speed of the main crack in different shapes of empty holes. When the empty hole is located at the fracture zone, the crack propagation direction can be effectively controlled [21].

By using AUTODYN code, Li et al. [22] established numerical models, studied the effect mechanism of empty holes on crack propagation behavior numerically, and found that empty holes have the arrest function on outgoing cracks. Guo et al. [23] took the empty hole as the control hole, the propagation characteristics of explosive stress wave and the expansion characteristics of the main coal seam cracks caused by explosion were investigated theoretically and numerically, and found that the presence of the control hole in coal seam under cumulative blasting improved significantly the permeability of coal seams. Chai et al. [24] compared the blasting processes with a double-cavity grooving and a four-cavity grooving and concluded that four empty holes can provide more compensation space and free surface and improve blasting performance. Rabczuk presented a meshfree method that does not require an explicit crack representation, the crack growth is represented discretely by activation of crack surfaces at individual particles in this method [25], different cracking criteria have been employed as rate dependent and rate independent constitutive and cohesive models [26], the comparison with experimental data showed that the method can predict experimental crack patterns and damage quite accurately, the crack was modeled by splitting particles located on opposite sides of the associated crack segments, and made use of the visibility method to describe the crack kinematics [27].

Most of the existing research studies focus on the function and parameter calculation of the empty hole in the cut blasting but few research studies on empty-hole directional blasting in the peripheral blasting. Based on the action mechanism of empty-hole directional blasting, the theoretical analysis and numerical simulation method are adopted, the influence of the spacing between the charge holes is analyzed, the calculated formula of the charge hole spacing is proposed, and the reasonable charge hole spacing of the blasting excavation of the Shijiazhuang South Ring Expressway was obtained.

## 2. Mechanism of Empty-Hole Directional Blasting

Empty-hole directional blasting is evolved from notched blasting; by arranging the empty holes between the charge holes of the peripheral blasting, the number of the openings on the excavation contour is increased, the integrity of the original rock layer is weakened, the primary rock stress is reduced, the antidamage capacity of the rock between the two holes is weakened, and make the rock between the charge hole and the empty hole more easily broken than the rock in other positions.

As a free surface, the empty hole can lower the resistance of blasting, reduce the clamping effect of rock during blasting, provide compensation space for rock expansion, and expand the crushing effect after blasting. When the stress wave generated by the explosion is transmitted to the vicinity of the empty hole, the stress wave is reflected, becomes a tensile wave, and enters the rock again, and the rock medium is under tensile stress. If the stress intensity is greater than the tensile strength of rock, the crack will first appear at the nearest position around the empty hole wall to the charge hole, and a new free surface will be produced after the crack appears, the subsequent stress wave will be reflected again on the new free surface to form a new tensile stress wave, and the superposition of the original tensile stress wave and the incident stress wave will cause the tensile stress concentration again. When the superposition value is greater than the tensile strength of the rock, the crack will reappear, cycling, until the cracks coalescence or crack arrest. The empty hole changes the stress distribution and stress value in the quasistatic stress field formed by explosive gas expansion pressure, makes the rock more vulnerable to shear failure, forms cracks between the charge hole and the empty hole first, and reduces the impact on the rock in other directions, which protects the stability of the surrounding rock and meets the requirements of the excavation.

Empty-hole directional blasting excavation, the shock wave generated after the initiation of the charge hole first forms a certain length crack around its periphery, then gradually attenuates to become a stress wave; when an empty hole is encountered, the stress wave is reflected, and the stress in the vicinity of the empty hole wall is significantly larger than that of no empty hole, which is the “empty hole stress concentration effect.” According to the formula of peak stress state around the empty hole, the maximum tensile stress appears in the connection direction between the charge hole and the empty hole, and cracks first appear along this direction. Under the guidance of the empty hole, the crack tip around the charge hole gradually deflects towards the empty hole. Finally, the crack coalescence in the direction of the two holes and realizes the directional fracture blasting. Simultaneously, the tangential compression in the direction of the vertical two-hole connection suppresses the crack propagation in the vertical direction and reduces the damage to the rocks outside the connection direction of the two holes.

In a word, empty-hole directional blasting weakens the antidamage force of rock in the direction of connecting the charge hole and empty hole, creates a new free surface, forms stress concentration in the wall of empty hole, guides the crack first propagates and coalescences between the charge hole and empty hole, and meets the requirements of engineering excavation. Meanwhile, the empty hole can guide the crack around the charge hole to deflect to the direction of the empty hole, suppress the development of cracks in other directions, reduce the impact of blasting on surrounding rock, and protect the stability of surrounding rock.

### 3. Influence of Charge Hole Spacing on the Effect of Empty-Hole Directional Blasting

In empty-hole directional blasting, when the spacing between the charge hole and the empty hole is small, the empty hole may be located within the crushing zone of the explosion, the rock between the two holes will be broken by the action of shock wave, and the detonation gas can escape from the empty hole in an instant, resulting in too many cracks between the two holes, unable to form a smooth excavation contour, and cannot play the main role of detonation gas in blasting crack propagation, resulting in reduced energy utilization of the explosive and excessive fragmentation of rocks. With the increase of the spacing, the guiding effect of the empty hole is gradually obvious. Under the stress concentration of the empty hole, the initial crack at the wall of the empty hole propagates and extends continuously, and it finally connects with the burst crack around the charge hole to form the coalescent cracks between the holes. When the spacing between the charge hole and empty hole is too large, the attenuation of explosive stress wave is relatively obvious, and the stress concentration effect generated at the empty hole wall will become weak, which is not enough to generate a directional crack of sufficient length in the rock mass, and the effective connection between the two holes cannot be formed, which cannot meet the requirements of excavation. Further analysis shows that the tangential stress decreases with the increase of the hole spacing after the stress concentration of the empty hole. The larger the spacing is, the smaller the tangential stress value is and the weaker the failure capacity of the rock is, and the directional fracture cannot be formed. Only when the empty hole is set in a reasonable position of the charge hole, can the empty hole play a guiding role effectively, form a directional crack, and meet the engineering requirements.

Figure 1 shows the relationship between empty hole spacing and crack propagation. Length  $a$  is the spacing between the charge hole and the empty hole, point  $A$  is any point around the charge hole, and point  $B$  is the point on the empty hole wall near the side of the charge hole, and  $d$  is the distance between  $A$  and  $B$ . When the charge hole is detonated, due to the stress concentration of the empty hole, the point  $B$  around the empty hole first reaches the tensile strength of the rock to form a crack, and the time it experiences is  $t_1$ . If there is no cracking at point  $A$ , the tangential stress will be released due to the cracking at

point  $B$ . The time for the stress unloading wave to propagate from point  $B$  to point  $A$  is  $d/c_u$  ( $c_u$  is the propagation velocity of stress wave). Let the time for the tensile stress of point  $A$  to reach the dynamic tensile strength of rock is  $t_2$ . If  $t_1 + (d/c_u) < t_2$ , the tangential tensile stress of point  $A$  is unloaded before reaching the dynamic tensile strength of the rock, and the shock wave energy generated by the explosion will fail to generate cracks at point  $A$ ; thus, the propagation of blasting crack in the protected rock mass is restrained. The larger the spacing between the charge hole and the empty hole, the longer the time of forming stress concentration at the point  $B$ , and the more likely cracks will appear in surrounding rock, which is unfavorable to the stability of surrounding rock.

Due to the addition of empty holes in empty-hole directional blasting, the stress of the primary rock is reduced, and the tensile strength of the rock is decreased. Only a small amount of explosive energy is needed to break the rock. At this time, if the detonation is carried out with the hole spacing without the empty hole, the explosive energy will be wasted and the surrounding rock will be damaged. Therefore, compared with ordinary peripheral blasting, the charge hole spacing of empty-hole directional blasting should be increased. Also, under the guiding action of the empty hole free surface, the crack around the charge hole is deflected toward the empty hole, and the number of cracks generated in the wall of the blasthole is significantly less than that of the ordinary peripheral blasting, which reduces the attenuation velocity of the load in the blasthole, and helps to form longer cracks between the charge hole and the empty hole, so that the initial crack can be propagated and penetrated only by a small explosive load, and a large charge hole spacing is realized.

In conclusion, reasonable charge hole spacing can guide the crack to initiation, propagation, and coalescence preferentially between the peripheral holes in empty-hole directional blasting, to form an ideal excavation contour. Meanwhile, the generation of other direction cracks can be suppressed, the impact of the blasting on the stability of the surrounding rock is reduced, and the directional blasting performance is improved.

### 4. Calculation of Charge Hole Spacing

From the above analysis, reasonable hole spacing is very important to achieve the effect of empty-hole directional blasting. At present, the determination of hole spacing is mainly obtained by numerical calculation [28], and there are not many theoretical calculation methods. In this paper, according to the theory of explosion mechanics and elastic mechanics, the influence of the empty hole on the blasting crack propagation is analyzed, and the theoretical calculation method of hole spacing for empty-hole directional blasting is obtained.

As shown in Figure 2, shock wave is generated after the initiation of the charge hole, which is continuously attenuated to the explosive stress wave. When it arrived at point  $P$ , the stress can be expressed as

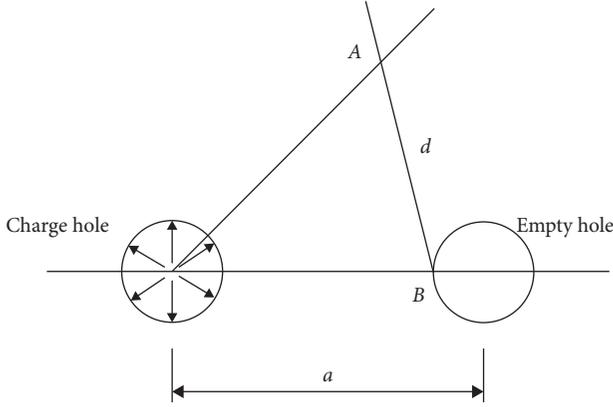


FIGURE 1: Relationship between empty hole spacing and crack propagation.

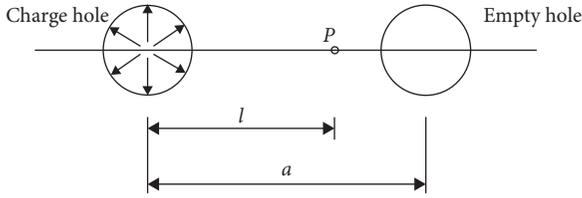


FIGURE 2: Layout of the empty hole in empty-hole directional blasting.

$$\begin{cases} \sigma_r = P_0 \left( \frac{r_a}{r} \right)^\alpha, \\ \sigma_\theta = b\sigma_r, \\ P_0 = \rho_0 D^2 \left( \frac{d_c}{d_b} \right)^6 \frac{l_e n}{8}, \end{cases} \quad (1)$$

where  $\sigma_r$  and  $\sigma_\theta$  is the radial stress and tangential stress in rock,  $P_0$  is the peak incident pressure of charge hole wall,  $r_a$  is the radius of charge the hole,  $r$  is the spacing from any point in the rock to the center of the charge hole,  $\alpha$  is the stress wave attenuation coefficient,  $b$  is the lateral stress coefficient,  $\rho_0$  is the explosive density,  $D$  is the explosive detonation velocity,  $d_c$  and  $d_b$  is the charge hole diameter and charge diameter,  $l_e$  is the hole charge coefficient, and  $n$  is the coefficient of increase in explosive pressure.

When the tangential stress  $\sigma_\theta$  of the point  $P$  is equal to the dynamic tensile strength  $\sigma_{td}$  of the rock, the crack length generated by the explosion is

$$l = \left( \frac{bP_0}{\sigma_{td}} \right)^{1/\alpha} r_a. \quad (2)$$

The stress wave continues to propagate to the empty hole, and the stress is obviously larger than that of the no empty hole due to the empty hole stress concentration effect [29]; the stress peak around the empty hole can be expressed as

$$\begin{cases} \sigma_{rr} = \frac{1}{2} \left[ (1 - k^2)(\sigma_\theta - \sigma_r) + (1 - 4k^2 + 3k^4)(\sigma_r + \sigma_\theta)\cos 2\theta \right], \\ \sigma_{\theta\theta} = \frac{1}{2} \left[ (1 + k^2)(\sigma_\theta - \sigma_r) + (1 + 3k^4)(\sigma_r + \sigma_\theta)\cos 2\theta \right], \\ \tau_{r\theta} = \frac{1}{2} \left[ (1 + 2k^2 - 3k^4)(\sigma_r + \sigma_\theta)\cos 2\theta \right], \\ k = \frac{r_b}{r_B}, \end{cases} \quad (3)$$

where  $\sigma_{rr}$ ,  $\sigma_{\theta\theta}$ , and  $\sigma_{r\theta}$  are the radial stress, tangential stress, and shear stress in rock after empty hole stress concentration,  $\theta$  is the angle between any direction and the two-hole connecting line,  $r_b$  is the radius of the empty hole, and  $r_B$  is the spacing from any point in the rock to the center of the empty hole.

It can be seen from formula (3) that when  $\theta = 0$  and  $\pm\pi$ ,  $\sigma_{\theta\theta}$  is the maximum value, that is, the maximum tensile stress occurs in the connection direction between the empty hole and the charge hole, and the expression is

$$\sigma_{\theta\theta} = \left( 1 + \frac{1}{2}k^2 + \frac{3}{2}k^4 \right) \sigma_\theta + \left( \frac{3}{2}k^4 - \frac{1}{2}k^2 \right) \sigma_r. \quad (4)$$

If the maximum tensile stress is greater than the dynamic tensile strength of the rock, the crack will initiate and propagate along the line connecting the two holes from the empty hole wall, and the crack generated under the stress concentration of the empty hole can also reach point  $P$  and is connected with the first stage crack, and a coalescence crack will be formed between the empty hole and the charge hole. At this time,

$$k = \frac{r_b}{r_B} = \frac{r_b}{a - l} \quad (5)$$

$$\sigma_{\theta\theta} = \sigma_{td}. \quad (6)$$

Therefore, it can be obtained from formulas (1) and (4):

$$\begin{aligned} \sigma_{td} = & \left[ b + \frac{1}{2} \left( \frac{r_b}{a-l} \right)^2 \right] b + \frac{3}{2} \left( \frac{r_b}{a-l} \right)^4 b + \frac{3}{2} \left( \frac{r_b}{a-l} \right)^4 \\ & - \frac{1}{2} \left( \frac{r_b}{a-l} \right)^2 \left] P_0 \left( \frac{r_a}{a-r_b} \right)^\alpha. \end{aligned} \quad (7)$$

By simultaneous equations (2) and (7), the spacing between the charge hole and the empty hole can be obtained; thus, the spacing between the two charge holes can be obtained.

Based on the above analysis, it can be seen that the spacing of charge holes in empty-hole directional blasting is related to the mechanical properties of rock (dynamic tensile strength and Poisson's ratio), detonation parameters of explosive (density and detonation velocity), charge structure, and aperture (including charge hole and empty hole). Therefore, the factor of rock, explosive, and aperture, especially the empty hole size, should be considered in the design of charge hole

spacing, and ensure that the spacing between the empty hole and the charge hole matches the empty hole aperture. The effect of the empty hole aperture on empty-hole directional blasting needs to be further studied.

## 5. Numerical Simulation of the Empty-Hole Directional Blasting Process

In order to determine the charge hole spacing of Shijiazhuang South Ring Expressway Tunnel, finite element software was used to simulate the directional initiation process of empty holes under different charge hole spacing, and reasonable charge hole spacing was proposed by analyzing the crack propagation behavior and the stress in the rock after initiation.

*5.1. Site Conditions and Construction Scheme.* Shijiazhuang South Ring Expressway Tunnel located in Hebei Province, China, 4900 m in length, belongs to tectonic denudation of middle and low mountain landforms. The mountain potential is relatively flat, the gullies are basically developed, most of them are “U” shaped, and the geomorphology is generally consistent with the undeveloped neotectonic movement in this area. The buried depth of most sections of the tunnel is 60~100 m, and the local depth is more than 150 m. The bedrock is mainly purplish red quartz sandstone and shale of Proterozoic Nansi Formation (Ptns). Rock mechanical parameters are shown in Table 1.

The field geological conditions and the mechanical properties of the rock show that the rock at the location of the tunnel has high strength and good integrity; it is difficult to excavate by ordinary peripheral blasting, and it may cause the overall rock caving. To ensure the safety of construction and achieve a better blasting excavation effect, empty holes are set up between the two charge holes and empty-hole directional blasting is adopted.

*5.2. Calculation Model and Material Parameters.* The mechanical model is established by ANSYS/LS-DYNA, and the stress value and crack state after explosive initiation are simulated and calculated. The finite element model is established with solid element SOLID164 of hexahedron. Since the interaction between the explosion shock wave and the structure is very complex, the following assumptions are based on in this paper: (1) the plane strain model is adopted in the calculation model without considering the influence of thickness. (2) The explosion of the explosive is completed instantaneously along the axial direction of the borehole, and the two charge holes are detonated simultaneously. All the boundaries of the model are nonreflective boundaries. Due to the complexity of the stress and strain around the charge hole, the meshing size is small, the number is large, and the meshes far away from the charge hole are relatively sparse, which can save calculation time and clearly show the development and evolution state of cracks.

The main calculation methods provided in ANSYS/LS-DYNA software are the Lagrange method, Euler method, ALE algorithm, and SPH algorithm [30]. In this simulation,

the ALE algorithm and its attached FSI are used to simulate and analyze the blasting of explosives in rocks. FSI can effectively solve the analog distortion caused by too much mesh distortion. In the preprocessing, the two meshes can cross each other, which make the calculation simpler, and are very suitable for solving the large deformation problem caused by blasting. Explosives and air are defined as fluids, using the Euler grid, rock using the Lagrange mesh, the explosive, air unit, and the structural unit are coupled to achieve the connection between each other, and use the keyword \*CONSTRAINED\_LAGRANGE\_IN\_SOLID to realize coupling.

In ANSYS/LS-DYNA, the simulation of fracture is achieved by setting the failure criteria. The key word \*MAT\_ADD\_EROSION was set with material parameters to define the failure criterion. In the process of calculation, once the set “failure criterion” of the model material reached, it would be automatically “deleted” and cracks or fractures would appear in the model immediately. In this paper, the key word \*MAT\_ADD\_EROSION was defined based on the above material parameters to simulate the dynamic expansion process of blasting cracks.

According to the tunnel site situation and calculation needs to establish the calculation model, the model size is 4000 mm × 3000 mm. One unit thickness is taken longitudinally, and the empty hole is arranged in the center and two charge holes are arranged symmetrically on both sides. The diameter of both charge holes and empty holes is 50 mm, as shown in Figure 3. The uncoupled charge is used, the uncoupling coefficient is 1.8, and the two blastholes simultaneously detonate. The blasting process was simulated when the charge hole spacing was 600 mm, 800 mm, 1000 mm, and 1200 mm, respectively, and the crack propagation behavior and rock stress changes after initiation at different spacing were analyzed; thus, the reasonable charge hole spacing was obtained.

In this simulation, the rock material model selects the H-J-C model. The strength of the H-J-C model is described by the normalized equivalent stress as

$$\sigma^* = [A(1 - D) + BP^{*N}] (1 + C \ln \dot{\epsilon}^*), \quad (8)$$

where  $\sigma^* = \sigma/fc'$  is the ratio of actual equivalent stress to static compressive strength,  $P^* = P/fc'$  is the dimensionless pressure,  $\dot{\epsilon}^* = \dot{\epsilon}/\dot{\epsilon}_0$  is the dimensionless strain rate,  $A$  is the standardized cohesion strength,  $B$  is the normalized pressure hardening coefficient,  $N$  is the pressure hardening index,  $C$  is the strain rate coefficient, and  $D$  is the damage factor.

Rock mechanical parameters are shown in Table 1.

The explosive is made of No. 2 rock emulsion explosive, and the parameters are shown in Table 2.

The explosive model selects the \*MAT\_HIGH\_EXPLOSIVE\_BURN constitutive model, which is included in LS-DYNA, and the JWL equation of state is used to describe the relationship between pressure and volume of detonation products. JWL equation is given as

$$P = A \left( 1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left( 1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E_0}{V}, \quad (9)$$

TABLE 1: Physical and mechanical parameters of rock.

Kinds of rock	Density (kN/m <sup>3</sup> )	Compressive strength (MPa)	Tensile strength (MPa)	Elasticity moduli (10 <sup>4</sup> MPa)	Poisson ratio
Sandstone	24.20	48.26	4.00	3.75	0.27

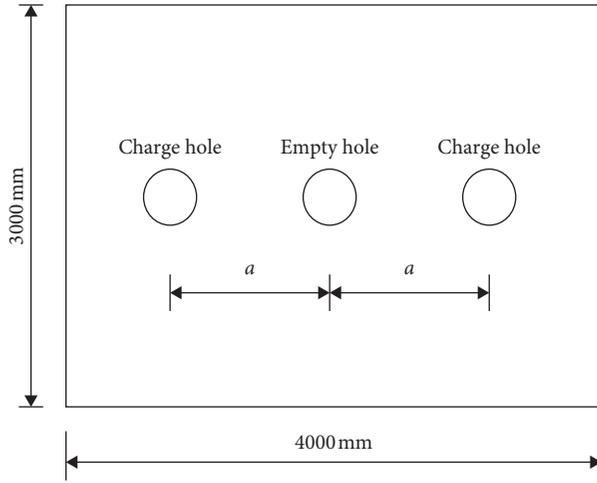


FIGURE 3: Calculation model of empty-hole directional blasting.

TABLE 2: Parameters of explosive and its equation of state.

Explosive parameters	Value	JWL equation of state	Value
Density (kN/m <sup>3</sup> )	12	A (GPa)	52.4
Detonation velocity (m/s)	4950	B (GPa)	0.768
CJ pressure (GPa)	6.125	R <sub>1</sub>	4.2
		B <sub>2</sub>	1.1
		ω	0.34
		E (GPa)	8.5

where  $P$  is the pressure of detonation products,  $V$  is the relative volume,  $E_0$  is the initial internal energy density, and  $A$ ,  $B$ ,  $R_1$ ,  $R_2$ , and  $\omega$  are the constants.

The \*MAT\_NULL model was used for the air material model. Its equation of state was defined through the keyword \*EOS\_LINEAR\_POLYNOMIAL. Its equation of state can be expressed as equation (10). The air material parameters are shown in Table 3.

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E, \quad (10)$$

where  $C_0$ ,  $C_1$ ,  $C_2$ ,  $C_3$ ,  $C_4$ ,  $C_5$ , and  $C_6$  are the input parameters.  $E$  is the internal energy parameter.

**5.3. Analysis of Simulation Results of Empty-Hole Directional Blasting.** An important index to test the simulation results is the error in the energy balance. The smaller the energy balance error is, the slower the convergence is and the more accurate the calculation results are. The error in the energy balance of this calculation is less than 1% [26]. Figure 4 shows the crack distribution after initiation with different spacing. The left column is the crack distribution in empty-hole directional blasting, and the right column is the crack

distribution in the case of ordinary peripheral blasting with the same charge hole spacing.

- (1) In the left column of empty-hole directional blasting, the crack length toward the empty hole around the charge hole is significantly larger than that in other directions, and the guiding effect of the empty hole leads the crack to propagate in the direction of the connection between the two holes at first, forming a longer directional crack, while the crack length in the other directions is shorter. The reason is that the existence of empty holes makes more energy concentrated on the direction between the charge hole and the empty hole, the diffusion to other directions is weakened, and the propagation of cracks in other directions is suppressed.
- (2) In the right column, the length and number of cracks between the two charge holes are superior to the other directions. Relative to the charge hole, the adjacent charge holes can function like empty holes, guiding cracks preferentially propagate between the two charge holes, resulting in a relatively small number of cracks in other directions.
- (3) Under the same hole spacing, the crack formed by empty-hole directional blasting are obviously longer than those of ordinary perimeter blasting. Even in Figure 4(g), the distance between the two charge holes is larger, and the crack is not penetrated, but under the effect of empty hole guidance, there are still longer directional cracks on both sides of the charge hole and the empty hole, and the direction basically coincides with the connection direction between the two holes. And that, the key parameter that affects the guidance of the empty hole is the spacing between the charge hole and the empty hole. When the spacing is small, the number of cracks between the two holes is large, there is no obvious direction, and the guiding effect of the empty hole cannot be effectively played (Figure 4(a)). The larger the distance is, the smaller the tangential stress after the stress concentration is, which is not enough to reach the fracture strength of rock; the guiding effect of the empty hole is weak, and it cannot form a coalescence crack between the two holes and cannot meet the requirements of excavation (Figure 4(g)).
- (4) Comparing the maximum stress in the rock after initiation, under the same hole spacing, the maximum stress value with the empty hole is much smaller than that without the empty hole (Figure 5). When the charge hole spacing is 600 mm, 800 mm, 1000 mm, and 1200 mm, the maximum stress value without empty hole was 45%, 55%, 42%, and 9%

TABLE 3: Air material and its equation of state parameters.

Density ( $\text{g/cm}^3$ )	$C_0$	$C_1$	$C_2$	$C_3$	$C_4$	$C_5$	$C_6$	$E$ (MPa)
$1.29E-5$	0	0	0	0	0.4	0.4	0	0.025

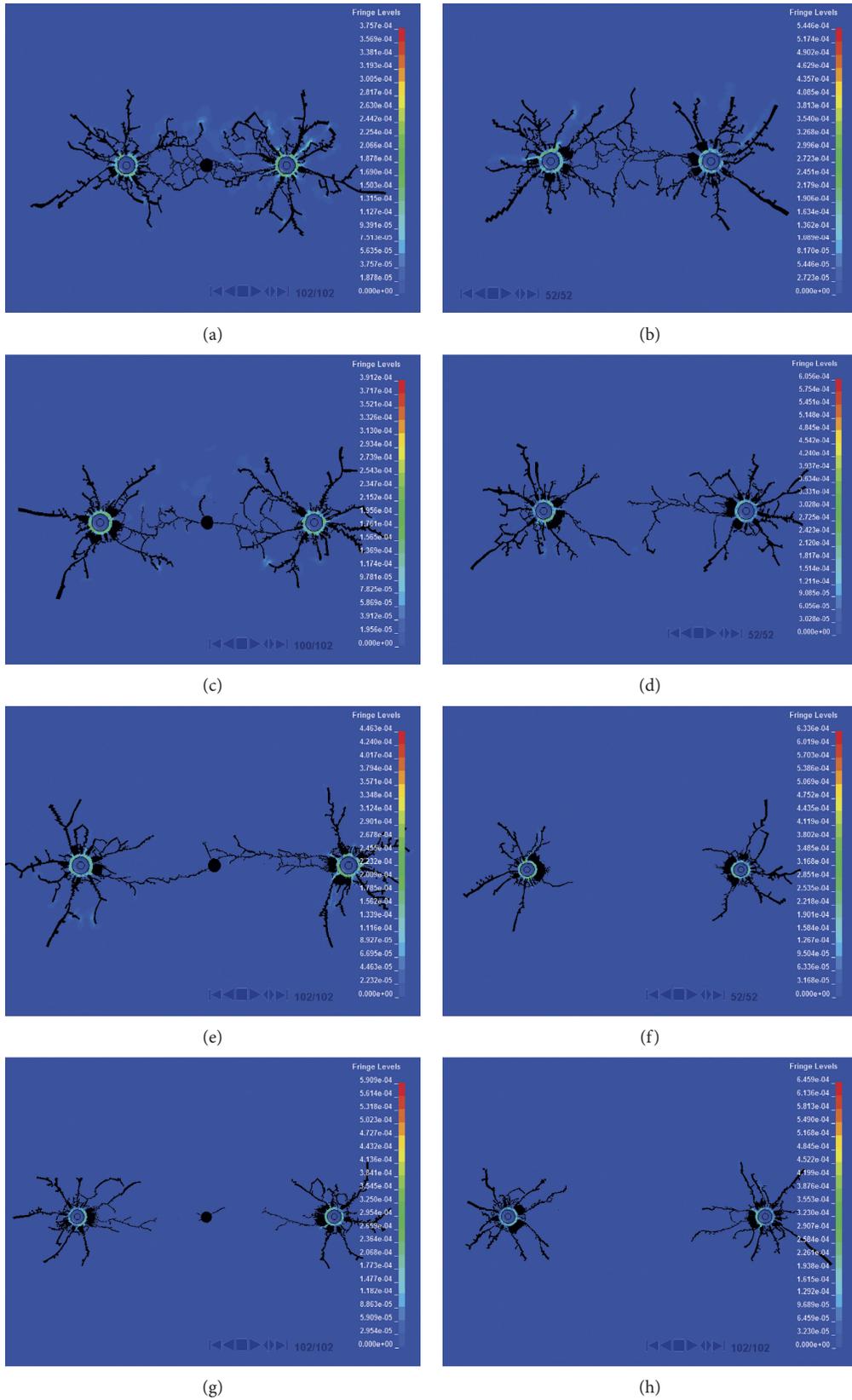


FIGURE 4: Crack distribution of different charge hole spacing. (a) 600 mm. (b) 600 mm. (c) 800 mm. (d) 800 mm. (e) 1000 mm. (f) 1000 mm. (g) 1200 mm. (h) 1200 mm.

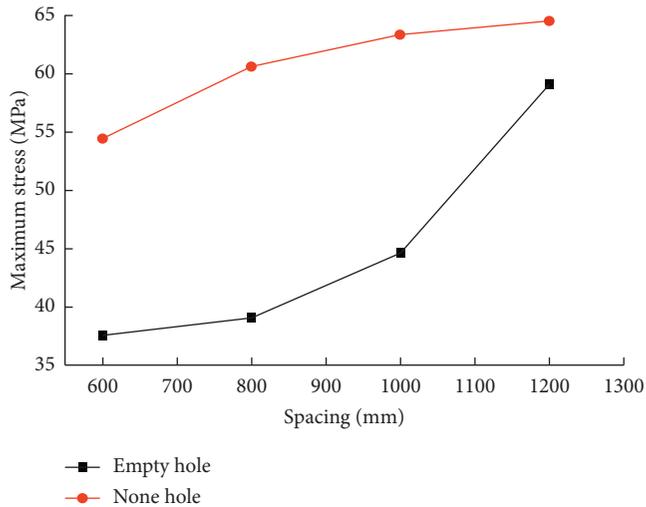


FIGURE 5: Maximum stress of different spacing.

higher than that with the empty hole, respectively. When the spacing is 80 mm, the difference between the two stress values is the largest, and the effect of the empty hole on protecting the stability of surrounding rock is the most obvious. With the increase of the hole spacing, the stress values generated by the presence or absence of empty hole are gradually close; the effect of the empty hole on the stress values of the surrounding rock is also smaller, and the empty hole effect on the crack propagation between the holes is also gradually weakened, which is consistent with the theoretical analysis.

- (5) In ordinary peripheral blasting, when the hole spacing is 600 mm, the cracks are mutually penetrated, but the number of cracks is more. At the spacing of 800 mm, the crack length between the two holes is maximum compared to other directions, but it failed to form an effective connection. When the charge hole spacing reaches 1000 mm and 1200 mm, the interaction between the two holes is very small. Therefore, the best charge hole spacing is 600–800 mm, which is consistent with the surrounding precracking hole spacing of 7–15*d* commonly used in engineering practice.
- (6) In empty-hole directional blasting, when the charge hole spacing is 600 mm, not only a plurality of coalescence cracks are formed between the charge hole and the empty hole but also a large number of random cracks are generated in other directions and extended to surrounding rock, adverse to the stability of surrounding rock. A coalescence crack is formed between the charge hole and the empty hole at the spacing of 800 and 1000 mm, but the number of the wing cracks on both sides of the main crack is more at 800 mm, the radius of the fracture zone around the two charge holes is larger, and the damage to the surrounding rock is more serious. When spacing is 1000 mm, there is only one

coalescence crack between the charge hole and the empty hole; there is no random crack in other directions, and the blasting effect is relatively good. At 1200 mm, the crack of the two charge holes is disconnected, which cannot meet the needs of blasting excavation.

According to the above analysis of the blasting crack propagation behavior, combined with the principle that blasting construction should simultaneously meet the excavation requirements and have the least impact on the stability of surrounding rock, the optimal charging hole spacing can be determined to be 800–1000 mm in empty-hole directional blasting of the tunnel.

*5.4. Comparison between the Simulation Results and the Theoretical Results.* Substitute the relevant parameters of Shijiazhuang South Ring Expressway Tunnel into the theoretical calculation formula, and  $b$  is 0.37,  $P_0$  is 1081 MPa, and  $\alpha$  is 1.63; substitute above parameters into formula (2), and the crack length generated by the charge hole after initiation can be calculated to be 422 mm. By formula (7), it is concluded that the spacing between the charge hole and the empty hole is 474 mm, that is, the spacing between the two charge holes is 948 mm. This result is in complete agreement with the numerical simulation results.

Through the selection of relevant models and the parameters, the blasting crack propagation behavior at different charge hole spacing is obtained. Only when the empty hole is located in a reasonable position, can the effect of empty-hole directional blasting be achieved. Yang [31] reported that the empty hole can effectively control crack propagation direction when it is located at the blasting fracture zone and is verified and enriched. At the same time, the numerical simulation shows that empty-hole directional blasting effect is the best when the charge hole spacing is 800–1000 mm, which is consistent with the spacing value obtained by the analytical solution, and the correctness of the theoretical analysis is verified. Formula (7) can be used as the basis for determining the charge hole spacing of empty-hole directional blasting in engineering site. This is different from Li et al.' [32] conclusion that the charge hole spacing is 0.4–0.6 m, and the reason is related to the value of rock parameters and the method of meshing in the model. However, all of them can provide certain guidance and reference for site blasting construction and design.

## 6. Conclusions

In this paper, the effect of the empty hole in directional blasting is theoretically analyzed, and the influence of charge hole spacing on blasting crack propagation behavior is studied; the charge hole spacing is calculated by theoretical analysis and numerical simulation, and it can be concluded that

- (1) Empty-hole directional blasting can reduce the stress of the primary rock, create a new free surface for explosive initiation, concentrate the stress on the

empty hole to form a guiding crack, reduce the occurrence of random cracks in other directions, reduce the impact of blasting on surrounding rock, improve the performance of peripheral blasting, and have a better blasting effect.

- (2) The spacing of charge holes is critical to the effect of empty-hole directional blasting. The spacing is small, the empty hole guiding effect cannot be fully exerted, the explosive utilization rate is low, and the random crack is more, which is unfavorable to the surrounding rock protection. The spacing is large, the stress concentration of the empty hole is weak, and the crack fails to penetrate effectively and cannot meet the excavation requirements. Reasonable charge hole spacing can guide crack initiation, propagation, and coalescence between the charge hole and empty hole, form ideal excavation contour surface, effectively protect the stability of surrounding rock, and better realize directional controlled blasting.
- (3) The spacing between the charge holes of empty-hole directional blasting is related to the mechanical properties of the rock, the detonation parameters of the explosive, the charge structure, and the aperture of the charge holes and the empty holes. In the design of charge hole spacing, it is necessary to ensure that the spacing between the empty hole and charge hole matches the aperture of the empty hole.
- (4) By analyzing the numerical simulation results of empty-hole directional blasting process under different spacings, it is concluded that the blasting effect is best when the charge hole spacing is 800–1000 mm in the Shijiazhuang South Ring Expressway Tunnel blasting excavation, which is consistent with the 948 mm of the theoretical calculation results. These results can provide a certain reference for the design and construction of the charge hole spacing under similar conditions.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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