Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 4924382, 9 pages
https://doi.org/10.1155/2019/4924382

Research Article

Key Blasting Parameters for Deep-Hole Excavation in an Underground Tunnel of Phosphorite Mine

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Received 9 September 2019; Accepted 18 November 2019; Published 5 December 2019

Academic Editor: Chongchong Qi

Ever increasing mine production capacity and mechanized operations enable advanced drilling equipment to be widely adopted in underground mines. In order to achieve satisfactory blasting performance in tunnel advance, there is a critical need to optimize the blasting technique to match the large deep-hole drilling capability. In this study, through theoretical analysis of tunnel blasting, the layout of cutting holes was found to be the key factor controlling the blasting performance. The deep-hole cutting effect was first investigated by analyzing the influence of the free surface of a hollow hole using the fluid-structure interaction modeling method in ANSYS/LS-DYNA. Then the rock dynamic evolution processes of blasting using a double-cavity grooving and a four-cavity grooving were compared and analyzed towards an understanding of the influence of the spacing and layout of cutting holes on the blasting performance. The comparison results show that four empty hole cut layouts yield larger effective free surface than that of the two empty hole cut layouts. This is because larger compensation space for breaking of rock and expansion of gas is more conducive to improving the energy utilization rate of explosives and thus improving the blasting performance and the footage of cyclic blasting. The results indicated that the blasting performance can be improved by reserving reasonable compensation space in the grooving area.

1. Introduction

Mining development is an indispensable part of China's economic construction, which has made great contributions to the economy. Tunneling blasting is the main construction method in the mine construction and production process. The success of excavation will directly affect the blasting effect of roadway excavation. In the blasting process of straight cut, the existence of empty holes can create good conditions for rock crushing in the cavity. Therefore, optimizing and improving the cut method is the main method to improve the blasting effect of mine tunneling.

In view of the construction of mines and tunnels under different geological conditions, many scholars have carried out a lot of research on the blasting of the trench and discussed the influence of cutting mode, cutting parameters, cutting diameter, and charging mode on blasting effect [1–6]. Shan et al. [7] proposed that the main cut and the working face have an angle, while the auxiliary cut was perpendicular to the free face. Man et al. [8] carried out the blasting test of face cutting mode in the Beishan pit exploration facility project in Gansu. The straight-eye grooving method is better than the single wedge-shaped grooving and composite wedge-shaped grooving method. The peripheral hole has a higher half porosity. Yang et al. [9] used numerical calculation and field test to study the double wedge deep-hole blasting, which provided reference for rock tunneling engineering. Ma et al. [10] simplified the design process of key parameters of roof cutting blasting with mathematical analysis method and determined the key indexes that affect the blasting design. Zhang [11] ranked the factors affecting the blasting vibration of the gutter by gray correlation analysis so as to optimize the design of the hollow hole blasting. Wang et al. [12] analyzed the explosive stress field of the first-order cut hole by numerical simulation and proposed that the increase of the central diameter empty hole made the stress wave peak value around the empty hole more than twice as much as that in the rock mass without empty hole. Zuo et al. [13] used high-speed photography to observe the throwing process and shape of the blasting rock mass under different hole diameters and proposed that the volume of the cavity was related to the diameter of the hole. Lin et al. [14, 15] studied the law of the cavity formation of the gutter and found that the rock would be ejected under the action of the gas generated by the high-pressure explosion.

In the above research, the mechanism and application of empty holes are discussed more, but the research on the influence of the number of empty holes on the blasting effect is less. In practice, the number and location of empty holes are closely related to the blasting effect. It is of great engineering significance to study the influence of the number of empty holes on the blasting effect of cutting. In this paper, the Houping phosphorite mine was used an engineering example. Firstly, the fluid-structure interaction modeling method in the finite element software ANSYS/LS-DYNA [16] was applied to analyze the effect of the free surface effect of the hollow hole in the hollow hole on the effect of deep-hole grooving. Then the comparative analysis of the dynamic evolution process of the cavity in the double-cavity gutter and the four-cavity gutter and the influence of the size and distribution of the free surface on the blasting effect were studied. Finally, the guttering technology for improving the deep-hole blasting of phosphate rock was optimized.

2. Analysis of Empty Hole Effect

The empty holes not only provide initial space for rock blasting but also convert the stress state around the rock as a free surface. After the detonation of the charging hole, the shock wave generated by the explosion quickly attenuates into a stress wave [17]. When the stress wave is transmitted to the empty hole, the reflection phenomenon will occur, leading to the increase of the stress wave at the wall of the empty hole, namely, the stress concentration effect of the empty hole [18–21]. Thereby the rock is cracked, broken, and thrown in the direction of the charge hole. The blasting effect is achieved. The stress wave generated by the two-hole explosion has a stress peak attenuation expression of

$$\begin{cases} \sigma_r = p_0 \left(\dfrac{r}{r_0}\right)^{-\alpha}, \\ \\ \sigma_\theta = -\lambda_d \sigma_r, \end{cases} \tag{1}$$

where σ_r is the radial stress of a certain point in the rock mass, MPa; σ_θ is the tangential stress of the explosion at a point in the rock, MPa; p_0 is the initial pressure acting on the hole wall after the explosion of the explosive, MPa; r_0 is the radius of the blasthole, m; r is the distance from a point in the rock to the center of the blasthole, m; and α is the stress wave attenuation coefficient. λ_d is the dynamic side stress coefficient.

It can be seen from Figure 1 that when the stress wave is transmitted to the wall of an empty hole, the stress of the wall will be greater than that in the case of no empty hole. That is to say, the more the number of empty holes is, the greater the guiding effect and expansion space provided by rock fragmentation.

3. Simulation and Analysis

Through the theoretical analysis of void effect, the mechanical parameters of rock are measured by using the triaxial apparatus in a laboratory. The ANSYS/LS-DYNA finite element program is used to simulate the blasting process of deep cut in tunnel excavation, and the blasting characteristics of deep cut in tunnel excavation are analyzed. The field test results are verified and compared with the simulation results, in order to optimize and improve the cutting technology of deep-hole blasting in phosphate mine.

3.1. Establishment of Numerical Model. Using the LS-DYNA finite element program, a three-dimensional model was built using cm/g/us. The model length was 70 cm, width was 70 cm, height was 450 cm, and the diameter of the blasthole was 40 mm. Figure 2 shows the numerical model corresponding to four empty holes and two empty holes.

3.2. Material Constitutive Equations and Parameters. The model includes three materials: explosive, rock, and air, among which the plugging material is rock. The anisotropic elastoplastic model in the LS-DYNA material model library was selected for the rock element. For air, the NULL model was used. For explosives, the MAT HIGH EXPLOSIVE_BURN model [22] and the JWL state equation were used, and the expression is

$$P = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E_0}{V}, \tag{2}$$

where P is the pressure, MPa; V is the volume change; and R_1, R_2, ω, B, and A are all material constants;

Dynamite, air, and rock mechanics parameters are shown in Table 1.

3.3. Results and Discussion

3.3.1. Effect of Cavity Cutting on Cavity Formation. Spatial and temporal evolution of surrounding rock stress of two and four cut holes are shown in Figures 3 and 4.

The cut blasting process can be clearly seen in Figure 3. At the moment of 240 μs, the cut area turns red, and the stress wave effect of the explosive is the largest, and it affects the whole area. At 280 μs, the stress waves of the first and third rows of charge holes are superimposed along the hole

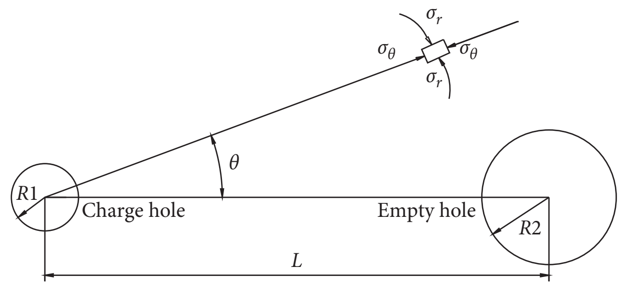

FIGURE 1: Analysis of stress concentration effect of voids.

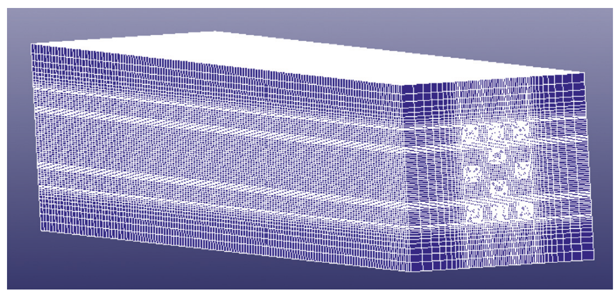

FIGURE 2: Numerical calculation model.

TABLE 1: Material parameters.

Explosive parameters	Density $\rho\,(g/cm^3)$	Detonation speed D	Pressure PCJ	Bulk modulus K	Shear modulus G	—
	1.0	0.36	$3.24E-02$			—
Air parameter	Density	Cutoff pressure pc	Dynamic viscosity coefficient MU	Relative volume TEROD	Elastic modulus YM	Poisson's ratio PR
	$1.2929E-03$					
Rock mechanics parameters	Bulk weight γ (g/cm^3)	Elastic modulus E (GPa)	Poisson's ratio	Uniaxial compression (MPa)	Tensile strength (MPa)	Cohesion C (MPa)
	2.73	55	0.36	65	4.5	45

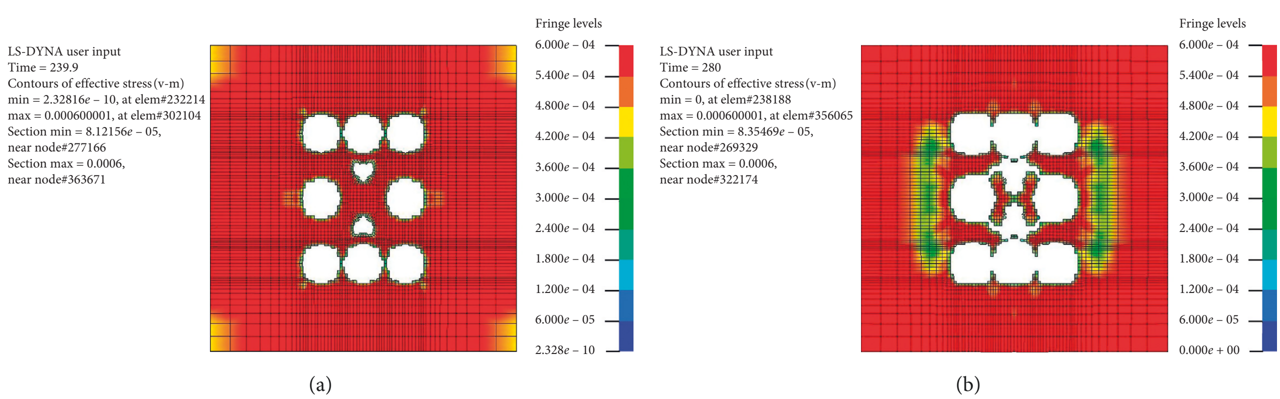

FIGURE 3: Continued.

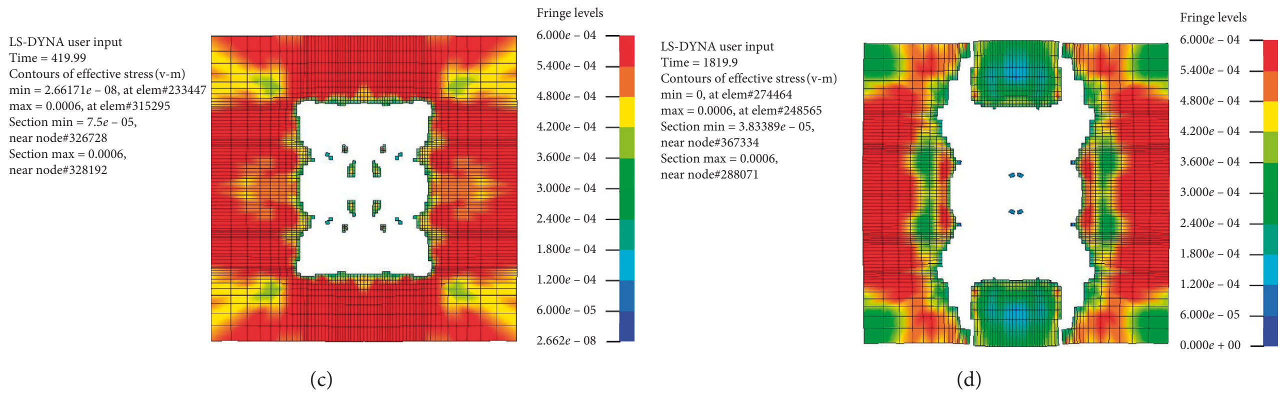

Figure 3: Spatiotemporal evolutionary cloud diagram of effective stress of two holes. (a) 240 μs. (b) 280 μs. (c) 420 μs. (d) 1820 μs.

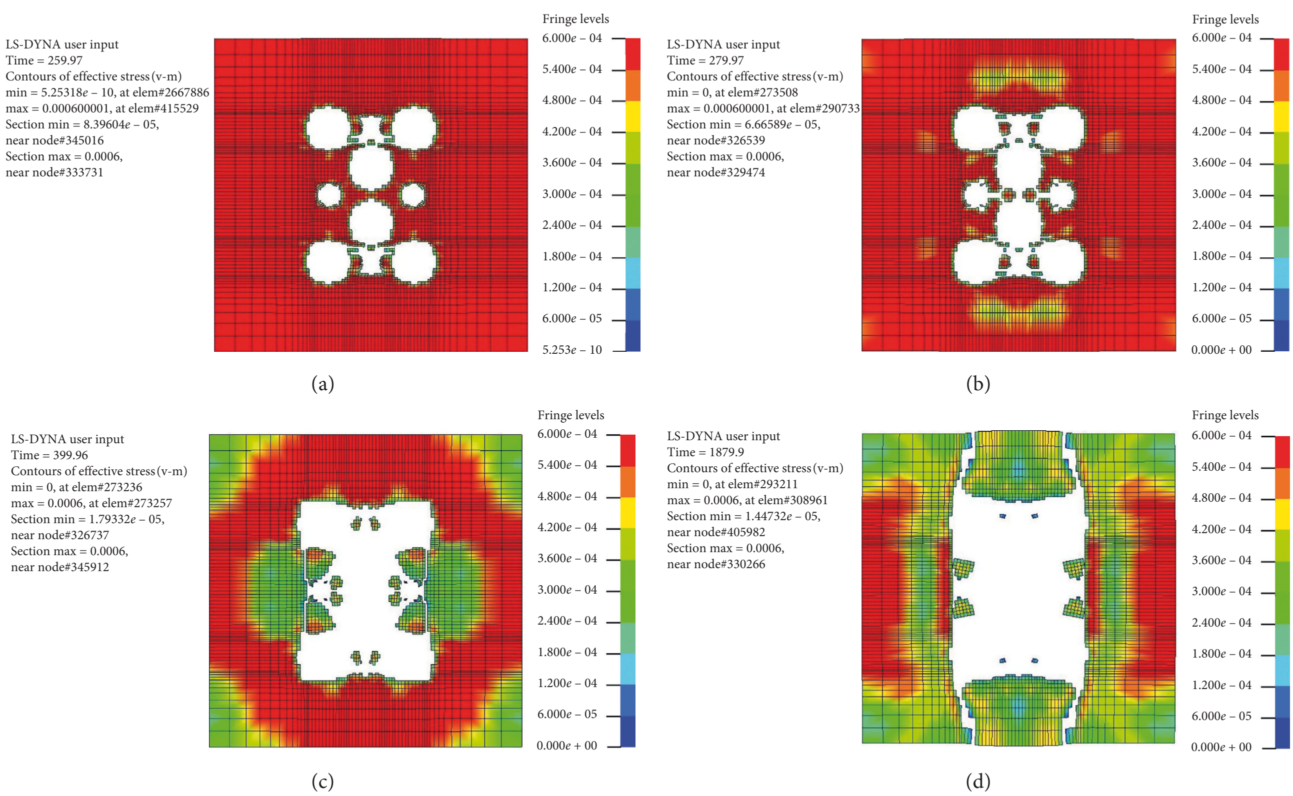

Figure 4: Temporal and spatial evolutionary cloud diagram of effective stress of four holes. (a) 260 μs. (b) 280 μs. (c) 400 μs. (d) 1879 μs.

coring line, causing the rock in the hole coring line to break first, and the rock in the hole area begins to rupture by the stress wave. At 420 μs, it can be seen from the figure that the violent compression phenomenon occurred in the explosive blasting process, the rocks near the upper and lower rows of charge holes are deeply damaged, and the gutter area is formed well. Since the circumference of the two holes in the center is not enough to provide enough space for the cavities of the eight charging holes, the rock mass in the gutter area has not ejected during the gutter process. At 1820 μs, the shape of the cut area has been preliminarily formed.

The spatial and temporal evolution cloud diagram of the effective stress in the four holes in Figure 4 shows that, at 260 μs, the stress superposition between the charging hole and the void hole is strengthened, and under the guidance of the void hole, the surrounding rock begins to crack along the hole connection center. At 280 μs moment, the two charge holes in the middle have the greatest degree of rupture and the holes on the connecting line of the charge holes are ruptured. It is proved that both charge holes and holes will rupture along the connecting line of the charge holes under the action of explosive load. At 400 μs, it is also observed that the rock in the area near the holes breaks along the core line of the holes. The upper and lower holes are deeply damaged, and the cutting area is well formed. It can be seen that, at 1879 μs, the core rock mass of the four-hole cut is all taken out, and only some rock masses around the hole are not stripped of the parent rock; if two charging holes are added on the periphery of the charge, the explosive will destroy the rock, break the rock away from the rock wall, and will generate more cutting space.

It can be seen that the empty hole has a great impact on the formation of the cavity. On the one hand, it can provide sufficient compensation space for the rock breakage in the cut area; on the other hand, it can serve as directional fracture between two holes, two explosive holes, and the hole and the explosive hole.

3.3.2. Effect of Different Hole Cutting on Stress Distribution of Surrounding Rock of Charge Hole. The stress distribution of the surrounding rock of the charge hole under different hollow hole gutter schemes is shown in Figure 5.

It can be seen from Figures 5(a) and 5(b) that the tensile stress and compressive stress of the loading section are characterized by stress jump and oscillation. As a whole, the area of relatively high compressive stress is near the charging center. In Figure 5(a), the compressive stress of the loading section of the four holes decreases from 503 MPa to 368 MPa, and a sudden change occurs in the compressive stress value of unit nos. 7 and 8, which increases from 337 MPa to 508 MPa. There is a stress anomaly, which is the result of the combined action of stress wave and explosive gas. In Figure 5(b), the stress value of several elements in the four holes is 0 compared with that in the two holes because the rock is in a crushing state under the action of high stress, which was related to the superposition effect of stress wave in the propagation process. The average compressive stress at the charging length unit of the four empty holes was 446.5 MPa, while the average pressure at the two empty holes was 350.75 MPa. Obviously, the compressive stress of the four holes was more advantageous than that of the two holes, which was conducive to broken rock mass. The tensile stress of two holes oscillates violently, but that of four holes maintains a low level, which was related to rational charging.

According to Figure 5(c), at the early stage of the plugging section, the maximum compressive stress of the four holes is 473 MPa, and the pressure is large before reaching the plugging medium and finally decreases to 18 MPa. The compressive stress of two holes and four holes shows a decreasing trend, which indicates that the propagation of the stress wave in the later stage of explosive reaction does not have enough energy to maintain, but the compressive stress of four holes has obvious advantages. As can be seen from Figure 5(d), the tensile stress value of the two holes does not appear at the same time with the compressive stress value, but the hysterical maximum compressive stress appears. Similarly, the pressure value at unit nos. 7 and 8 decreases from 46 MPa to 29 MPa because the sharp reduction of compressive stress leads to the reduction of Poisson's effect of the unit and the accompanying tensile stress. To sum up, the rock near the free surface of the plugging section is dominated by tensile stress failure. The stress value does not show a decreasing trend of attenuation, and the type of action is different at different plugging locations.

It can be seen from Figure 5(e) that the maximum compressive stress of the two holes and four holes in the bottom section of the hole appeared in the contact area between explosive and rock, and the maximum compressive stress of the four holes was 503 MPa larger than the 407 MPa of the two holes. As can be seen from Figure 5(f), the tensile stress value at unit nos. 6, 7, and 8 of the two empty holes was 0, which was caused by the explosion stress wave near the initiation point of these three units and the compression rock of explosive gas, so the compressive stress was increased, and the tensile stress was 0. From the size of the element, it can be inferred that the compressive stress and tensile stress of the rock 50 cm away from the bottom of the hole are both large, which were not effective for tunnel blasting and will seriously affect the next construction operation and blasting effect. The tensile stress of the four holes was the result of stress wave action in Sections 1–4 of unit number, where the tensile stress value at fourth unit was 4 MPa less than that on both sides, which was related to the superposition factor of the stress wave. The tensile stress at element number 6 was 0 because the element is near the initiation point. From the stress data, it can be seen that the four-hole cutting blasting scheme has more advantages. It is more conducive to improve circular footage and blasting effect.

4. Application Analysis

4.1. Site Conditions and Scheme. The phosphorite mine in Houping member of Shukongping mining area is a sedimentary phosphate block rock deposit, which occurs in the first section of Sinian Doushantuo formation and is a hidden ore body. The occurrence of the ore layer is stratiform, consistent with the occurrence of the rock layer, and the whole is monoclinal structure, slightly undulating, and relatively gentle occurrence.

In order to study the physical and mechanical properties of mine rock, the theoretical analysis and numerical simulation method were used to optimize the design to determine the cutting scheme of straight hole with four holes. The cutting scheme of four empty straight holes on the project site is shown in Figure 6, and the relevant blasting parameters are shown in Table 2.

4.2. Analysis of Application Effect. The comparison between the original project blasting and the four-hole blasting scheme at the engineering site is shown in Figure 7.

In general, the average unit consumption of explosives used in the two-hole blasting scheme is 2.054 kg/m^3, which is higher than the rated standard of 1.86 kg/m^3 for drift excavation blasting. The average footage of single cycle excavation is 2.966 m, the utilization rate of blast holes is not more than 80%, the depth of residual holes is up to 60 cm, and the blasting effect and tunnel forming are poor. In the four-hole blasting scheme, the average unit explosive consumption is 1.809 kg/m^3, the average footage of

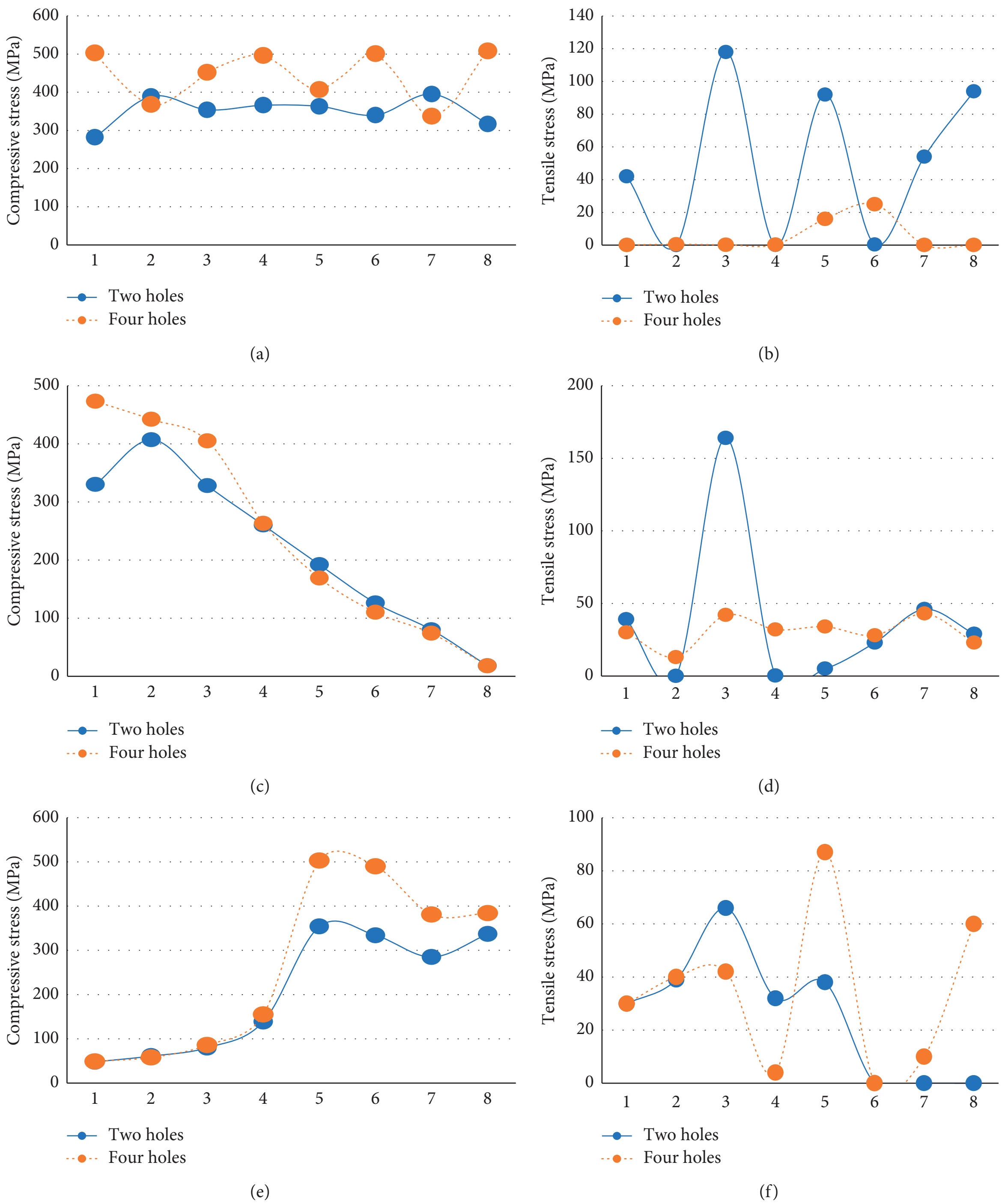

Figure 5: Stress curve of each part of the blasthole. (a) Pressure stress in the charging section. (b) Pulling stress in the charging section. (c) Blocking section compressive stress. (d) Pulling section tensile stress. (e) Rock compressive stress at the bottom of the blasthole. (f) Rock tensile stress at the bottom of the blasthole.

single cycle excavation is about 3.4 m, and the utilization rate of blast holes is up to 92%. From the scenes two empty hole and four empty hole blasting effect data, without changing the total charge and the number of blast holes, the blasting effect of the four holes is obviously better than that of the two holes, and images taken from the representative can be seen that the rock mass under the four-hole blasting scheme is relatively uniform. From the uniform fragmentation, it can be seen that the hole distribution mode and millisecond blasting time of the section are reasonable, which is convenient for shoveling and transportation.

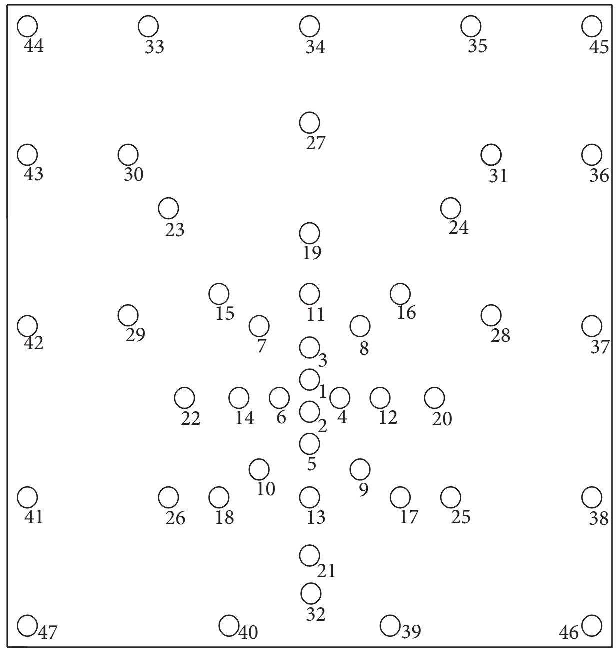

Figure 6: Four-hole blasting scheme (the numbers in the figure represent the hole number).

Table 2: Explosion parameters of the four-hole slotting scheme.

Gun hole name	Parameter		
	Number of holes	Single hole charge (kg)	Detonator section
Slot hole	10 (12, 7~4)	3	MS1
Auxiliary hole	18 (15~32)	2.5	HS6
Peripheral hole	15 (33~47)	2.1	HS10

Nos. 3–6 are large empty holes. The detonator segments 1-2, 7-8, and 9–14 are, respectively, MS1, MS9, and HS2. The detonator segments from 15 to 18 are HS3, 19 to 22 are HS5, 23 to 26 are HS6, 27 to 29 are HS7, and 30 to 32 are HS8. The detonator segments of 33~43 are HS9, while those of 44~47 are HS10.

(a)

Figure 7: Continued.

(b)

Figure 7: Comparison of on-site blasting effects. (a) Original plan blasting effect. (b) Four-hole blasting effect.

5. Conclusion

In this paper, it is theoretically analyzed that the existence of empty holes can provide initial space for rock blasting, and then the formation process of the cavity in the cutting area is simulated by numerical simulation. Finally, the following conclusions are obtained by combining with the site blasting test:

(1) Compared with two holes, the arrangement of the four holes optimizes the cutting area of the blasting, and the sufficient empty hole space provides sufficient expansion compensation space for rock blasting.

(2) The existence of voids and explosive holes changes the stress state of the gutter region, and the complex dynamic effects are generated under the action of charge explosion. The preferential fracture in the stress concentration area reflects the stress concentration of the pores.

(3) For the blasting of the gutter area, the four empty holes play the role of energy constraint and guidance to the charge of the inner layer and free surface to the external charge, which jointly promote the formation of the cutting area.

(4) The main causes of the formation of the tunnel cavity are the compressive stress and explosive gas of the deep-hole cutting blasting, and the tensile stress has no obvious superiority in this process.

In this study, the influence of the cutting mode on the blasting effect of tunnel excavation gives that the four-hole cutting mode is better than the two-hole cutting mode. In order to prove the advantages of the scheme, it should be applied to the roadway with different cross-section sizes to further verify the advantages of its blasting effect.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The support from the National Natural Science Foundation of China (Grant no. 51709257) and Science and Technology Research Project of Hubei Education Department (Grant no. D20171506) is sincerely appreciated.

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