Analysis of the Cracking Mechanism of an Elliptical Bipolar Linear-Shaped Charge Blasting

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Received 12 December 2020; Revised 3 January 2021; Accepted 1 February 2021; Published 12 February 2021

Academic Editor: Ma Jianjun

1.Introduction

In recent years, in order to meet the production and safety requirements, directional fracture-controlled blasting technology is being widely adopted in engineering fields such as tunnel blasting, slope excavation, roof cutting and pressure relief, coal seam permeability enhancement, etc. While realizing a pre-cracking expansion in the scheduled direction, it can satisfy the stability of the coal and rock mass in the nonscheduled direction. Common directional fracture-controlled blasting techniques can be classified into three categories: Type I is the slotted shaped blasting, by cutting in a specific direction of the charge tube, and the slotted tube is used to redistribute the explosive energy, thereby achieving the blasting effect of directional fracture [1]; Type II is the slotted shaped blasting, by presetting the grooves on the wall of the blast hole, stress concentration occurs at the tip of the grooves due to the effect of the explosion load, thus achieving preferential propagation of the crack in the direction of the prefabricated grooves [2]; Type III is the blasting of a shaped charge [3], which uses a detonation wave to squeeze the charge cover to form a shaped charge jet that penetrates the coal and rock mass and achieves the purpose of directional fracture in the direction of the shaped charge jet.

In recent years, many scholars have conducted substantial research on the abovementioned three types of shaped energy blasting. Song et al. [4] optimized the decoupling coefficient of the shaped charge by carrying out numerical analysis and compared the results thus obtained...
with those obtained from field tests. It was concluded that the blasting effect is better when the decoupling coefficient is between 1.67 and 2. Luo and Shen [5] theoretically analyzed the crack initiation mechanism and propagation law of the directional fracture controlled blasting of rocks and verified the results using model tests. The results of model test and field test showed that the directional fracture blasting with shaped charge was a better method for tunnel excavation. Ma et al. [6] studied the directional presplitting energy blasting technology and surrounding rock control technology using various research methods, and tested it in the case of a coal seam and a composite roof. Their results show that the directional presplitting energy blasting technology can effectively control the damage evolution in the roof rock. Wang [7] and Yang et al. [8, 9] studied the dynamic evolution of blasting and cracking patterns of different charge structures of slotted cartridges by conducting experiments and numerical simulations, optimized the structure of the blasting and cracking patterns of slitting medicine packages, and revealed the dynamic evolution of blasting and cracking patterns of slotted cartridges. Guo et al. [10, 11] conducted numerical simulation on the cracking process of a coal seam to understand the crack propagation mechanism, and based on field experiments, explored the effect of charge structure on the permeability enhancement of deep-hole-shaped charge blasting coal seam. Based on the theory of the two-way-shaped tension blasting, He et al. [12] carried out a numerical simulation and field tests to study the directional presplitting blasting of a tunnel and estimated the optimum blast hole spacing. Li et al. [13, 14] realized a three-dimensional numerical simulation of the shaped charge using smoothed particle hydrodynamics (SPH) and coupled the SPH method with the finite element method (FEM) to achieve the effect of a shaped jet penetration into a steel plate. Yue et al. [15] combined numerical simulations and experiments to study the effect of the blasting hole spacing on the crack propagation caused by the blasting of slotted cartridges, and the results showed that the smaller the hole spacing was, the better the crack propagation was. Zhang et al. [16] applied the elliptical bipolar linear-shaped charge to a roadway and, in combination with field tests, optimized the parameters for a D-type energy-gathering tube. Li et al. [17] obtained the optimal decoupling coefficients of elliptical bipolar linear-shaped charge by performing numerical simulations and experiments. The values thus obtained are 3.20 from the numerical simulation and 3.43 from the experiment, which are essentially very similar to each other. Ma and An [18] performed a numerical simulation of blasting a slotted cartridge in rock using the Johnson–Holmquist material model to verify the effect of the directional fracture of the energy-gathering fracture. The abovementioned works have primarily researched the shaped charge blasting from the perspectives of theory, experiment, and numerical simulation. However, they focus mostly on the study of the shaped charge blasting of the metal powder-type cover. The focus on charge blasting research on PVC shaped charge cover is less.

In view of the complexity of the explosion problem, in order to discuss the mechanism of cracking induced by charge blasting of the elliptical bipolar linear-shaped charge blasting, a theoretical analysis has been carried out in this work on the mechanism of charge accumulation, the formation of a charge jet, and the mechanism of rock mass cracking and expansion under charge accumulation in the case of an elliptical bipolar linear charge blasting. In addition, experiments have been conducted to analyze the effect of the charge blasting, and the ANSYNS/LS-DYNA simulation program has been used for conducting the numerical analysis of the rock-blasting mechanism of shaped charge blasting.

2. Analysis of the Mechanism of Shaped Blasting

2.1. Mechanism of Energy Gathering. There are different types of shaped charges depending upon their structures, and as a result, there are different kinds of shaped charge hoods. As a key research object, this article focuses on the elliptical bipolar linear-shaped charge pack commonly used in tunnel-shaped charge blasting. It consists of a combination of a PVC energy-gathering tube and an emulsified explosive to squeeze the charge cover after the explosive exploding to form the energy jet that penetrates the rock body. After a certain penetration depth, stress redistribution occurs in the energy accumulation direction due to the effect of the explosion load. The rock mass shows a tensile effect such that the blasting effect of the directional fracture is easier to form in the energy-gathering direction. In the nonenergy-gathering direction, due to the buffer effect of the outer shell and air, the peak value of the explosion impact load acting on the wall of the blast hole is reduced. As a result, the damage of the protection rock mass in this direction is reduced. Figure 1 shows a schematic diagram of the principle of the elliptical bipolar linear-shaped charge blasting and its charge structure.

2.2. Mechanism of the Formation of the Shaped Jet. Assuming that the explosive detonation mode is a simultaneous detonation at the center of the axis, the propagation of the detonation wave can be regarded as a plane wave propagation. After the detonation, the wave surface of the detonation wave continues to propagate outward. The detonation wave begins to squeeze the drug mask, forming a shaped jet and pestle body. According to the Pugh, Eichelberger, and Rostoker (PER) theory, ignoring the strength of the energy-gathering hood and the speed difference between the inner and the outer layers of the hood, and assuming that each microcell body instantaneously obtains the same constant compressive velocity, the process of the collapse of the energy-gathering hood can be represented, as shown in Figure 2. When the detonation wave propagates from point A to point P, the microelement A collapses to point B on the symmetry axis. Consequently, a focused jet is formed at the front end, and a pestle body is formed at the rear end. The microelement body C arrives on the opposite axis later than the microelement body A. When the shaped jet is completely formed, it is continuously
stretched and becomes partially disconnected from the pestle due to the speed difference. In the charged direction of the shaped charge structure, when the detonation wave acts on the charge cover, it moves to the center by squeezing the charge cover and collides with the center to form a charge flow. It is assumed that the angle formed by the action direction of the detonation wave is consistent with the angle of the energy-gathering cover. The load value before the collision is maintained at the initial average detonation pressure, \( P_0 \). Assuming that the angle formed by the detonation wave action direction is consistent with the angle of the shaped cover and the pre-collision load value remains at the pressure, \( P_0 \), the post-collision pressure, \( P \), can be written as the following:

\[
P = 2P_0 \cos \alpha.
\]

The diffusion of the shaped jet can be approximated by the analysis of the secondary flow under the assumption of instantaneous detonation. The pressure, \( P_1 \), of the shaped jet before it enters the rock can be expressed as [19] the following:

\[
P_1 = \left( \frac{R_0}{r} \right)^{\gamma - 1} P_0
\]

where \( R_0 \) is the equivalent charge radius of the shaped charge structure, \( r \) is the blast hole radius, and \( \gamma \) is the power exponent, which for a column symmetry structure is \( \gamma = 2 \).

2.3. Cracking and Expansion Mechanism of the Shaped Charge Blasting. In the process of shaped charge blasting, the shock wave first reaches around the hole and causes the rock mass around the hole to break. As the energy of the shock wave continues to reduce, the shock wave becomes a stress wave acting on the rock and causes tangential tensile stress. When this tangential tensile stress is greater than the dynamics tensile strength of the rock, radial cracks appear that continue to propagate under the quasi-static pressure of the explosive gas. Assuming that blasting is an ideal adiabatic closed space, the average detonation pressure, \( P_0 \), of the explosion is given by the following:

\[
P_0 = \frac{1}{2} \frac{1}{(1 + k)} \rho_0 D^2,
\]

where \( k \) is the isotropic index of the detonation product that is generally taken as 3, \( \rho_0 \) is the explosive density, and \( D \) is the velocity of the detonation wave.

In the direction of energy-gathering, the effect of the energy-gathering jet on the wall of the blasting hole will stimulate an impact load. After the collision, there is a pressure amplification factor \( \lambda \). Substituting equations (1) and (3) into equation (2), the load value, \( P_1 \), on the wall of the rock-blasting hole is

\[
P_1 = \frac{\lambda R_0 \cos \alpha}{\tau (1 + k)} \rho_0 D^2.
\]

From equation (4), it can be seen that the peak load in the direction of energy accumulation is related to the cone angle and the radial decoupling coefficient of the energy-gathering cover.

In the direction of the noncharged energy, since the distance between the energy-gathering cover and the wall of the blasting hole is different, in order to simplify the analysis, the shaped charge pack is taken to be equivalent to a round grain with the same dose. The pressure of the detonation gas is very high at the beginning of the explosion. As it expands continuously, the pressure of the detonation gas decays rapidly. When the uncoupled charge is large, the detonation gas can be analyzed on the basis of the two-stage expansion law. The pressure, \( P_2 \), of the explosion gas, as the gas expands toward the wall of the blasting hole, is given by

\[
P_2 = P_k \left( \frac{P_0}{P_k} \right)^{\gamma/\gamma_k} \left( \frac{V_0}{V} \right)^{\gamma},
\]

where \( P_k \) is the critical pressure; \( \gamma \) is the adiabatic index, and generally takes a value of 1.2~1.4; \( V_0 \) is the volume of the

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**Figure 1:** Schematic diagram showing the principle of the elliptical bipolar linear-shaped charge blasting and its charge structure.

**Figure 2:** Schematic diagram showing the crushing process of the energy-gathering hood.
In the shaped charge blasting, owing to the shaped charge effect in the shaped charge direction, a crack with a certain initial length is formed, and thus the load value required for initiating and propagating the crack is reduced during the stress wave action phase. Under the action of the same stress wave, the length of the crack in the direction of energy accumulation is longer. Hence, the load value required for initiating and propagating the crack in the direction of energy accumulation is relatively smaller. Under the same pressure, the length of the crack in the direction of energy accumulation driven by the explosion gas is longer, and the length of the crack generated in this direction is longer than that in the nonenergy accumulation direction.

3. Analysis of the Shaped Charge Blasting Test

3.1. Test Description. In order to study the mechanical response mechanism of the medium to the explosive action of the elliptical bipolar linear-shaped charge pack, a plexiglass plate test, as shown in Figure 3, was carried out. Assuming that the force is a plane strain structure, vertical radial, and parallel radial strain gauges were arranged every 100 mm along the center of the hole toward the energy-gathering direction, the 45° direction, and the nonenergy-gathering direction, where the strain gauges parallel to the radial direction were odd numbered and those perpendicular to the radial direction were even numbered, as shown in Figure 3(a). The model test material was a plexiglass plate of dimensions 1200 mm × 600 mm × 12 mm. The super dynamic strain testing instrument was the DH8302 dynamic signal test and analysis system. The on-site patch layout is shown in Figure 3(b). The dynamic mechanical parameters of the plexiglass plate are as follows [7]: longitudinal wave velocity $C_L = 1260$ m/s, transverse wave velocity $C_T = 1260$ m/s, optical constant $c = 85$ μm²/N, elastic modulus $E_d = 6.1$ GPa, and Poisson’s ratio $\mu = 0.31$. The explosive was a no. 2 emulsified explosive; the material of the energy-gathering tube was PVC, and the detonator center detonation method was adopted. In the explosion process, due to the rapid expansion of the explosive gas from both sides of the blast hole, the dynamic response of the plexiglass plate was mainly due to the explosion shock wave.

3.2. Test Results and Analysis. Figure 4 shows the crack propagation diagram after blasting. It can be seen from the figure that as a result of the explosion shock wave, because the dynamic tensile strength of the medium was much smaller than the initial shock wave of the explosion, a certain crushing area was formed around the blast hole. With the attenuation of the shock wave, it became a stress wave that acted on the medium to cause a hoop tensile stress, resulting in radial cracks. At the same time, the initial crack in the energy accumulation direction was longer due to the penetration of the energy accumulation jet. If the blast hole is blocked, the initial crack will continue to propagate forward under the quasi-static action of explosive gas, so that the adjacent blast holes will be connected. Shaped blasting made
full use of the energy-gathering effect to achieve the directional fracture effect of the acting medium.

Figure 5 shows the strain-time history curves for each measuring point after the explosion. Since the exact moment of the actual explosion cannot be captured, the abscissa is only a relative action time. It can be seen from the figure that in the energy-gathering direction, the strain value of the CH01 measuring point exceeds the test range value and the peak value of the strain is much greater than 100,000 με. CH02 measuring point is subjected to tensile and compression alternating load. This measuring point was at the same position as the CH01 measuring point, and thus the peak strain value is also larger. CH03 measuring point is observed to be mainly affected by the shock compression waves, whereas CH04 measuring point has just started to be subjected to tensile stress. On comparing results corresponding to CH01 and CH03 points or CH02 and CH04 points, it can be seen that with the propagation of the stress wave, the peak load decay rate is faster. In the nonfocusing direction, CH05 and CH06 measuring points near the blasting hole are mainly subjected to compressive stress. Since CH06 measuring point is perpendicular to the radial direction, theoretically, it should primarily be tensile under the action of the radial compressive stress waves. This is because the sampling frequency was too low, and thus negative strain values could not be collected. Alternatively, the placement of the strain gauge might not have been completely perpendicular to the stress wave propagation direction. As the shock wave continued to propagate forward, the CH07 measuring point was subjected to a compressive load. The CH08 measuring point was first subjected to tensile stress and then to compressive stress. The peak stress of CH07 and CH08 measuring points is much smaller than the CH05 and CH06 measuring points. This shows that the decay rate of the shock waves in the nonfocusing direction is also faster. Two stress peaks are observed at the CH05 and CH06 measuring points. The second peak can be understood to be a result of the reflected compression wave caused by the detonation wave acting on the energy-gathering hood lagging behind the initial detonation wave in the nonfocusing direction. The CH09 and CH10 measurement points in the 45° direction are similar to the CH05 and CH06 measurement points in the 90° direction with the same spacing. However, compared to the CH01 and CH02 measuring points with the same spacing, their peak load pressure is relatively small. Since the peak value of the compressive strain in the energy-gathering direction exceeds the range of the compressive strain, it is impossible to know how many times the peak value in the energy-gathering direction corresponded to a peak value in the nongathering direction. However, it had a significant energy-gathering effect due to the effect of the energy-gathering jet in the energy accumulation direction.

4. Numerical Simulation

4.1. Numerical Model. The experiment failed to capture the formation process of the shaped charge jet and the dynamic response of the entire acting medium. Thus, in order to study the dynamic response mechanism of the elliptical bipolar linear-shaped charge blasting, the ANSYS/LS-DYNA simulation program was used to establish a numerical calculation model. Due to the large deformation in the vicinity of the explosion, the SPH algorithm can be used for solving the errors caused by the Lagrange and arbitrary Lagrange-Eulerian (ALE) grid distortions. In order to improve the calculation efficiency, the Lagrange algorithm was used in the far zone of the
Figure 5: Continued.
explosion. The SPH–FEM coupling algorithm was used for realizing the large deformation calculation in the near explosion area and for improving the calculation efficiency. In order to reduce the effect of the stress wave reflection at the coupling contact, binding nodes were used at the coupling contact to achieve energy and force propagation. The radius of the model was 60 cm, the radius of the hole was 2.1 cm, and the energy-gathering tube and the shell were 2 mm thick and made up of PVC material. A schematic of the calculation model is shown in Figure 6. In order to reduce the influence of the boundary reflecting waves, nonreflecting boundary constraints were imposed on the boundary.

The explosive used in the calculation model was the no. 2 emulsified explosive commonly used in civilian explosions. In the numerical model, the material model of the explosive was characterized by MAT_HIGH_EXPLOSIVE_BURN. The relationship between the pressure and volume after the initiation of the explosive is described by the Jones-Wilkins-Lee (JWL) equation of state:

\[
p = A \left(1 - \frac{\omega}{R_1V}\right) e^{-R_1V} + B \left(1 - \frac{\omega}{R_2V}\right) e^{-R_2V} + \frac{\omega E}{V},
\]

where \( p \) is the pressure, \( V \) is the volume, \( A, B, \omega, R_1, \) and \( R_2 \) are the basic parameters of the equation of state, and \( E \) is the initial internal energy per unit volume. The constitutive parameters of the explosive and those of the equation of state can be obtained by fitting. The resultant values are listed in Table 1.
Table 1: Parameters corresponding to the no. 2 rock emulsion explosive used in the numerical simulation.

| $\rho$ (kg·m$^{-3}$) | $v_0$ (cm·µs$^{-1}$) | $P_C$ (GPa) | $A$ (100 GPa) | $B$ (100 GPa) | $R_1$ | $R_2$ | $w$ | $E$ (GPa) |
|----------------------|-------------------|-------------|--------------|--------------|-------|-------|-----|-----------|
| 1.14                 | 0.32              | 2.918       | 2.461        | 0.1026       | 7.177 | 2.4   | 0.069| 4.2       |

The energy-gathering tube is made of PVC material. The detonation wave squeezes the PVC at the energy-gathering groove to form an energy-spraying jet. Owing to the penetration of the energy-spraying jet, the rock undergoes a directional fracture in the energy-accumulating direction. Because the explosion is a complex and short-term process involving high temperature, pressure, and speed, the gas phase occurs in the PVC after forming a shaped charge jet that penetrates into the rock. At this time, the PVC has little effect on crack propagation [12]. After the PVC phase transition, the quasi-static effect of the gas in the blast hole can be increased. It is difficult to accurately describe the dynamic mechanical response mechanism of PVC by numerical simulation. Hence, the influence of temperature on the PVC pipe was ignored, and a plastic-hardening model related to strain rate was used. Using the Cowper–Symonds model for taking the effect of the strain rate into account, a factor related to the strain rate was introduced in the yield stress. The yield stress, $\sigma_y$, can be expressed as

$$
\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{1/p}\right] \left(\sigma_0 + \beta E_p \varepsilon_P \right),
$$

where $\sigma_0$ is the initial yield stress and $E_p$ is the plastic-hardening modulus and is given by $E_p = (E_0 E_{tan}/ (E_0 - E_{tan}))$, where $E_0$ is the elastic modulus and $E_{tan}$ is the tangent modulus. $\dot{\varepsilon}$ is the loading strain rate; $C$ and $P$ are the Cowper–Symonds strain rate parameters, which are determined by the strain characteristics of the material; $\varepsilon_P$ is the effective plastic strain; $\beta$ is the hardening parameter, and has a value $0 < \beta < 1$. The follow-up hardening model and the isotropic-hardening model were selected by adjusting the hardening parameters.

It is difficult to accurately describe the constitutive model of a rock. The commonly used constitutive models for it are Holmquist–Johnson–Cook (HJC) model, Taylor–Chen–Kuszmaul (TCK) model, Riedel–©"homa–Hiermaier (RHT) model, etc. In this study, the HJC constitutive model that is able to reflect the high strain, high strain rate, and high pressure effect of the medium has been selected. Its equivalent yield strength is a function of the damage and the equivalent stress-strain rate, and can be expressed as

$$
\sigma^* = \left[A(1-D) + BP^*\right] \left(1 + C \ln \varepsilon^*\right),
$$

where $\sigma = (\sigma/\sigma_0)$ is the ratio of actual equivalent stress to the static yield strength, $P^* = (P/P_0)$ represents the dimensionless pressure, $\varepsilon^* = (\varepsilon/\varepsilon_0)$ represents the dimensionless strain rate, $D$ is the damage factor, $A$ is the normal viscosity coefficient, $B$ is the pressure hardening coefficient, and $C$ is the strain rate coefficient.

The damage factor is derived from the accumulation of the equivalent plastic strain and the plastic volume strain and is expressed as

$$
D = \sum \frac{\Delta \varepsilon_p + \Delta \mu_p}{D_1 (P^* + T^*)^{D_2}}
$$

where $\Delta \varepsilon_p$ and $\Delta \mu_p$ are the equivalent plastic strain increment and the equivalent volume strain increment, respectively, $T^*$ is the dimensionless tensile force, and $D_1$ and $D_2$ are the damage constants. The basic physical parameters of PVC and rock are listed in Table 2.

4.2. Analysis of the Shaped Jet Formation. In the simulation, after the explosive center was detonated, the detonation wave continued to propagate outward, forming a shaped jet by squeezing the shaped mask, as shown in Figure 7. At 3.5 $\mu$s, the detonation wave propagated to the sharp corner of the energy-gathering hood and began to squeeze the energy-gathering hood. At 5.5 $\mu$s, stress concentration could be observed on both sides of the energy-gathering hood, forming a squeezing effect that lead to the formation of the energy-gathering jet. At 7.1 $\mu$s, stress redistribution occurred in the detonation wave in the energy-gathering hood. The high stress was mainly concentrated at the center of the blast hole and the peak stress load reached 864 MPa. The explosive gas then expanded continuously, pushing the outer shell and the shaped jet to expand outward. At 9.2 $\mu$s, the head of the shaped jet was about to collide with the wall of the blasting hole and the part where the shell and the shaped hood were connected was about to reach the wall of the hole. There was no obvious advantage in time for the shaped jet to penetrate the rock that was relative to the connected parts, to collide with the rock. If the blasting radius was too small, the shaped jet did not form effectively and the part of the pestle body did not separate from the shaped jet. Therefore, the decoupling coefficient of the charge structure also had a significant influence on the shaped blasting effect.

4.3. Spatiotemporal Distribution of the Load on the Blasting Hole Wall. Figure 8 shows a distribution diagram of the peak load acting on the wall of the blast hole, whereas Figure 9 shows a distribution diagram of the peak pressure acting time on the wall of the blast hole. Due to the peak pressure of the detonation wave acting on the rock, there would be a pressure amplification effect. It can be seen from the figure that the peak load acting on the wall of the blast hole was significantly larger than the peak pressure of the detonation wave. In the direction of energy accumulation, owing to the penetration of the formation of the energy accumulation jet, the peak load on the hole wall was significantly higher than that of the nonenergy accumulation direction and the pressure peak was 1.64 times larger than that in the nonenergy accumulation direction. At the same time, the peak load in the directions between 0 and 30° was lower than that in the noncharged direction, mainly because
it used energy to form the shaped jet to act on the wall in the 0° direction. It can be seen from Figure 9 that the peak acting time of the borehole wall load in the energy-gathering direction is earlier than that in the non-gathering direction. However, the acting time has no obvious advantage. This is because the shaped jet was not formed effectively, which is consistent with the conclusion obtained from Figure 7.

4.4. Analysis of the Initial Crack Formation. SPH particles were used for describing the plastic rheological state of coal and rock masses in the vicinity of the explosion. It is difficult to show the initial cracks in the form of macro-cracks. Therefore, in this work, the formation mechanism of the initial cracks has been presented by plotting their penetration depth and stress distribution. Figure 10 shows the propagation process of the initial crack. At 10.9 μs, the explosion had fully reacted and formed a shaped jet. The shock wave had acted on the wall of the blasting hole in the shaped energy direction, which strongly squeezed the surrounding medium in the shaped energy direction. At this time, the rock mass in the shaped energy direction was damaged by the intense compression and shear. Two symmetrical initial cracks were formed, and a certain amount of initial damage was also produced in the blasting hole wall in the directions between 0° and 45°. At 17.6 μs, the shell had collided with the wall of the blast hole, causing stress concentration in the non-concentrating direction, and an initial damage also occurred in this direction. At the same time, the charge jet and the pestle penetrated continuously in the charge direction, resulting in the initial crack further expanding in this direction. Subsequently, owing to the combined action of the detonation gas and the stress wave, the medium was subjected to radial compression and caused hoop tension. When the hoop tensile stress inside the medium was greater than the tensile strength of the medium itself, the initial crack continued to expand.

4.5. Analysis of the Propagation Characteristics of the Stress Wave. Figure 11 shows the stress-time history curves of each of the measuring points at an interval of 0.1 cm along the wall of the hole in the energy-gathering and the non-energy-gathering directions. It can be seen from the figure...
that the peak load decay rate is very fast along the center of the blast hole, whether it is in the energy-gathering or nonenergy-gathering direction, indicating that a large amount of impact explosion energy was consumed near the blast hole. There are two obvious load peaks at the measuring point in the nonconcentrating direction. The second load peak is mainly due to the superposition of the reflected compression waves caused by the shock wave acting on the concentrating cover in the nonconcentrating direction. Because it lagged behind the initial shock wave propagation, the second load peak appears, and its value is much smaller than the first load peak, which is consistent with the results of the experiment.

In order to study the propagation characteristics of the stress waves in the mid-distance region of the shaped blasting, a measuring point was selected at an interval of 5 cm outward from the center of the blast hole in the 0° shaped gathering direction, 45° direction, and 90° noncharged gathering direction, as shown in Figure 12(a). The stress peak corresponding to each measuring point is shown in Figure 12(b). It can be seen from the figure that the peak value of the stress wave in the far zone in the explosion is not too different in the energy-gathering direction, the 45° direction, and the nonenergy-gathering direction. The explosion shock wave consumed a lot of energy after crushing the medium in the near area due to impact. Thus, the attenuation of the stress wave in the mid-range region was essentially identical.

4.6. Comparative Analysis. The rock mass is crushed and destroyed by the shock wave, and the shock wave load is attenuated as the propagation distance increases. When the shock wave load is less than the dynamic compressive strength, the rock is mainly affected by the stress wave, which causes the rock to compress radially and produce tangential tension. When the tangential stress is greater than the dynamic tensile strength of the rock, radial cracks are generated. In shaped charge blasting, due to the shaped charge flow in the shaped charge direction, a crack having a certain initial length is formed. Depending on the initial conditions of fracture mechanics, in the stress wave action phase, the shaped charge direction reduces the value of the load required for crack initiation and propagation. Therefore, the
crack propagation length generated in the energy-gathering direction is greater than that in the nonenergy-gathering direction. Thus, the results of the theoretical analysis are consistent with the experimental results. Owing to the penetration of the shaped jet, the peak value of the initial explosion load in the shaped charge direction is significantly larger than that in the noncharged direction, and the theoretical, experimental, and numerical results are consistent. In the vicinity of the charge explosion, a large amount of shock explosion energy is consumed in the crushing area. Therefore, regardless of the direction of charge accumulation or noncharge accumulation, the shock wave attenuation rate is faster. In the nonfocusing direction, a second stress peak appears due to the reflected compression wave. However, its value is smaller than the initial shock wave peak. The experimental and numerical analysis results are thus consistent.

5. Conclusions

(1) Due to the effect of the shaped jet, the load value of the initial shock wave in the shaped energy direction is significantly larger, by about 1.64 times, as compared to the nonshaped energy direction. In addition, the peak load acting time is earlier than in the nonshaped energy direction.

(2) A large amount of shock explosion energy is consumed in the near-field of the charge explosion due to the crushing area. Regardless of the direction of charge accumulation or noncharge accumulation, the shock wave attenuation rate is faster in the near explosion area, and the stress wave attenuation rate is slower in the far area of the explosion. The difference in the explosion load in the middle and remote areas is small.

(3) In the nonfocused direction, owing to the effect of the reflected compression waves, the superimposed effect of the reflected compression waves makes the nonfocused direction lag behind the initial shock wave, and a second stress peak appears. However, its value is smaller than the initial shock wave peak.

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 authors thank the financial support from the National Natural Science Foundation of China (Nos. 51678164 and 51478118), Innovation Project of Guangxi Graduate Education (YCSW2020040), the Guangxi Natural Science Foundation Program (2018GXNSFDA138009), the Guangxi Science and Technology Plan Projects (AD18126011), the Scientific Research Foundation of Guangxi University (XTZ160590), and the project supported by GDHVPS (2019).

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