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Study on the formation of rock mass cracks based on the interval charge structure with constant blasting energy

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Abstract

In order to solve the problem of energy concentration of traditional continuous charge and poor quality of pre-splitting surface in deep hole pre-splitting blasting, this study aims to explore the efficient and uniform utilization of explosion energy by optimizing the structure of axial interval charge under the premise of constant total blasting energy, so as to form a continuous and flat pre-splitting surface. Under the constraint of constant total charge and total charge length, the method of combining theoretical analysis with numerical simulation is adopted. The three-stage fracture mechanism of interval charge is explained from the mechanical theory, and the double-hole pre-splitting blasting model is established based on LS-DYNA software. Three kinds of interval charge schemes of three sections, four sections and five sections are designed systematically, and the blasting effects are compared. The numerical simulation results show that the number of charge segments plays a key role in regulating the energy distribution and stress field morphology under the condition of constant total energy. Through comparison, it is found that the four-stage charge scheme achieves the best balance between energy concentration and dispersion, and can form a continuous, uniform and lasting tensile stress field, which is most conducive to the straight penetration of the pre-splitting surface. The three-stage and five-stage schemes have the defects of uneven distribution and insufficient driving force, respectively.

Keywords

Pre-Splitting Blasting; Interval Charge; Seam Formation Mechanism; Blasting Energy Constant

1. Introduction

In deep hole pre-splitting blasting engineering, the design of charge structure is the key to determine the efficiency of blasting energy utilization and the forming quality of pre-splitting surface. Although the traditional continuous charge structure is easy to construct, its energy is excessively concentrated in the aperture of the gun, which easily leads to excessive crushing of the rock mass on the hole wall and causes energy waste. At the same time, the energy is unevenly distributed along the axial direction of the borehole, and it is difficult to form a continuous and flat directional pre-splitting surface between the boreholes[1][3]. Therefore, how to realize the rational distribution and efficient utilization of energy in the axial direction of the blast hole by optimizing the charge structure under the constraint of constant total explosion energy has become the core scientific problem and engineering problem to improve the effect of deep hole pre-splitting blasting.

In view of the above problems, scholars have carried out research from different angles. Cai Feng and Liu Zegong[4] studied the effect of uncoupling charge on the attenuation of stress wave energy, and found that increasing the uncoupling coefficient will reduce the total energy of stress wave. Through the model test, Yang Guoliang[5] et al.found that there is an optimal radial uncoupling coefficient to make the damage distribution of the specimen most uniform and the energy utilization rate optimal. The study of Guo Zhidong[6] et al.showed that the uncoupled charge can prolong the action time of detonation pressure and make the energy transfer more uniform. These studies provide an important theoretical basis for the regulation of blasting energy by charge structure.

The axial interval charge structure can effectively change the release and transmission path of explosion energy by introducing interval media such as air and water to segment the explosive[7]. The structure can not only inhibit the excessive crushing of the hole wall, but also make the stress wave produce multiple superposition and prolong the action time of the detonation gas by segmented initiation, which is more conducive to promoting the directional penetration of the pre-splitting surface. However, how to determine the optimal number of charge segments to achieve the most uniform and efficient distribution of explosive energy in rock mass under the premise of constant total charge and charge length, so as to form a high-quality pre-splitting surface, remains to be further studied. Therefore, a model of interval charge structure based on constant total blasting energy is established. By analyzing the effective stress distribution and crack development in the rock around the borehole after blasting, the spatial distribution of the initiation energy release point is regulated under the constraint of constant total energy, so as to realize the distribution and utilization of energy in the axial direction of the borehole and improve the effect of deep hole pre-splitting blasting.

2. Mechanism of pre-splitting fracture of rock mass under interval charge

The pre-splitting crack formation under interval charge is a dynamic evolution process with the synergistic effect of explosion stress wave and detonation gas and the orderly participation of multiple explosion sources[8]. Its core feature is that the crack initiation-propagation-penetration process is regulated by the segmented release of axial energy. Based on the theory of rock dynamics and fracture mechanics, the process can be divided into three key stages : initial crack initiation stage, crack directional propagation stage and pre-splitting surface penetration stage. The energy transfer mode, mechanical mechanism and crack evolution of each stage are directly affected by the structural parameters such as the number of charge segments and the interval length.

2.1. Initial crack initiation stage

The core driving force of the initial crack initiation stage is the multi-source explosive stress wave generated by the interval charge. The control mechanism is ' multi-source superposition and uniform initiation ', which avoids the problem of chaotic distribution of initial cracks under continuous charge. Multiple independent detonation sources are formed by axial segmented arrangement of interval charge. The detonation wave generated by the initiation of each charge section is buffered and shaped by the air gap, and transformed into a stress pulse with moderate strength and prolonged action time. According to the superposition principle of stress wave propagation, the stress waves generated by adjacent charge sections form a superposition effect at different positions in the axial direction of the hole wall, which makes the circumferential tensile stress distribution along the axial direction of the hole wall more uniform. The tensile strength of the rock is only 1/10~1/20 of the compressive strength. When the circumferential tensile stress exceeds the dynamic tensile strength (σtd) of the rock, the initial microcracks initiate along the tangential direction of the hole wall. Based on the theory of elastic mechanics, the distribution law of the circumferential tensile stress (σθ) of the hole wall can be described by the modified thick-walled cylinder theory :

$$\sigma_\theta = \frac{K^2 - 1}{K^2 + 1} \cdot P_d \tag{1}$$

In the formula, K is the radial uncoupling coefficient, and P_d is the impact pressure after the attenuation of the hole wall under the interval charge. Combined with the axial segmentation characteristics of the interval charge, the P_d at different positions in the axial direction of the hole wall is determined by the single-stage charge energy and the superposition effect of the stress wave in the adjacent section. The P_d value is higher in the corresponding area of the charge section, and the corresponding area of the interval section is slightly increased due to the superposition of the stress wave. Finally, the variance of the σ_θ distribution in the axial direction of the hole wall is reduced by 30%~40% compared with the continuous charge.

2.2. Crack directional propagation stage

The core driving force of the directional propagation stage of the crack changes from the explosion stress wave to the quasi-static pressure of the detonation gas, and its control mechanism is reflected in the ' gas wedge efficiency and directional extension '. The core is to extend the action time of the detonation gas by interval charge, and guide the crack to propagate preferentially along the direction of the hole connection.

After the initial crack initiation, the detonation gas expands slowly through the air gap, continuously fills the hole wall and the initial crack channel, and forms a stable quasi-static pressure field. According to the ' gas wedge effect ' theory of detonation gas, the crack propagation force (F) generated by gas pressure acting on the crack wall can be expressed as :

$$F = P_g \cdot A \tag{2}$$

In the formula, P_g is the quasi-static pressure of the explosive gas, N ;A is the stress area of the crack wall. The attenuation rate of P_g is significantly reduced by the energy storage effect of the air gap, and the action time is extended by 30%~50% compared with the continuous charge, which provides sufficient power for the continuous expansion of the crack.

2.3. Pre-splitting surface penetration stage

The core mechanism of the penetration stage of the pre-splitting surface is ' stress field coordination and uniform penetration '. The space-time distribution of energy is controlled by the interval charge to ensure that the crack penetrates uniformly along the axial direction and forms a continuous and flat pre-splitting surface to avoid the defects of local penetration and overall discontinuity. With the increase of crack length, the quasi-static pressure field of detonation gas forms a synergistic effect with the original stress field of rock mass and the stress field of adjacent blast holes. According to the crack coalescence criterion of fracture mechanics, when the stress intensity factor (K_I) of the main crack produced by the two blast holes reaches the fracture toughness (K_{IC}) of the rock, the crack coalescence occurs. By optimizing the number of charge segments and the interval length, the stress field between the two blast holes presents a ' continuous and uniform ' distribution characteristic : the tensile stress in the midpoint area of the hole connection is provided by the superposition of the stress wave of the two blast holes and the pressure of the detonation gas, and its value is maintained at 1.2~1.5 times of σ_{td}, which ensures that the crack tip continues to meet $K_I \geq K_{IC}$.

3. Numerical simulation of rock mass blasting based on constant total blasting energy

3.1. Numerical model

Based on the engineering geological conditions of 22010 working face in Chaochuan Mine, a two-dimensional numerical model of double-hole pre-splitting blasting with guide holes was established by using LS-DYNA explicit dynamic analysis software. The model includes two charge holes and one guide hole located in the center of the connection line to simulate the stress superposition and crack penetration process of rock mass between holes. The model size is set to be length × width = 6.0 m × 23.0 m, the length of the charge section is 16m, the length of the sealing section is 5m, the diameter of the cartridge is 70mm, the diameter of the borehole is 95mm, the radial decoupling coefficient K = 1.36, and the charge hole spacing is 2.0m. The model as a free surface is applied with non-reflective boundary conditions, as shown in Fig.1.

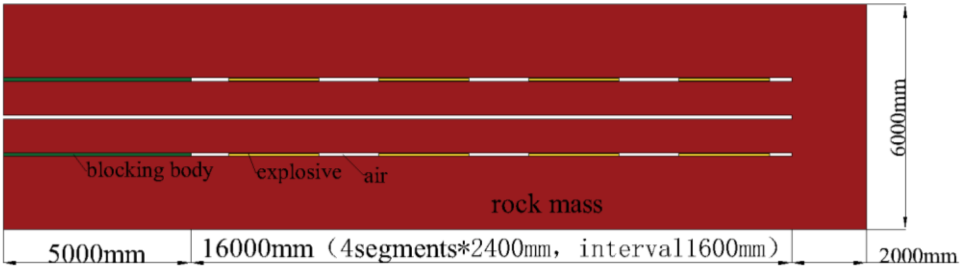


Fig 1. Numerical calculation model of charge section 4

The model includes four materials : rock, explosive, air and blockage. The rock material adopts the RHT damage model which can reflect the dynamic fracture behavior of rock at high strain rate. The explosive material is described by MAT _ HIGH _ EXPLOSIVE _ BURN model combined with EOS _ JWL state equation, and the parameters correspond to the mine emulsion explosive used in the field. The air gap between the hole and the cartridge is simulated by MAT _ NULL material model and linear polynomial state equation EOS _ LINEAR _ POLYNOMIAL, and the model of plugging material is * MAT _ SOIL _ AND _ FOAM material model.

3.2. Comparison scheme design of interval charge structure

Combined with the actual drilling parameters of the 22010 working face of Chaochuan Mine, the drilling depth is 31 m, the sealing length is 15 m, the effective charge length is 16 m, and the theoretical calculation of the total charge is 19.2 kg, the linear charge density is 1.2 kg / m. Under the constant constraint of the total charge energy, three axial interval charge structure schemes are designed. The core variable is the number of charge segments. By changing the spatial distribution of explosives in the axial direction of the blast hole, the regulation law of the energy release point layout on the pre-splitting effect is explored. Different schemes are shown in Table 1.

Table 1. Simulation scheme

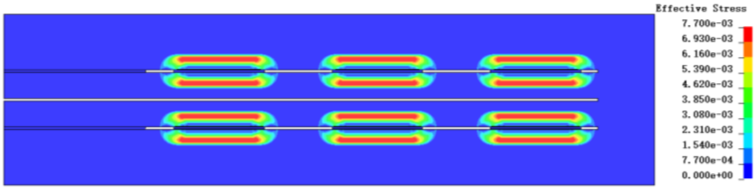
Scheme	charge quantity/kg	single charge length/m	charge section number	block length/m
1	19.2	3.2	3	5
2	19.2	2.4	4	5

3	19.2	1.92	5	5

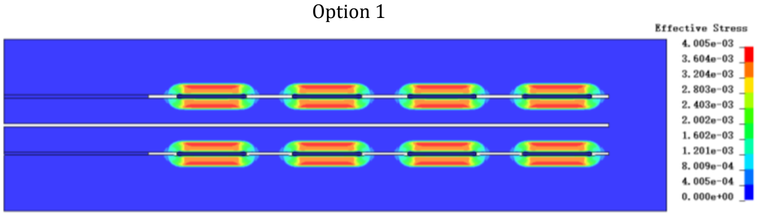
In order to eliminate the interference of other factors on the simulation, the design of each scheme should ensure that the total charge length is 16 m and the total charge amount is 19.2 kg, and only the number of charge segments and the interval length are adjusted. The first charge of each scheme is 1 m away from the boundary of the sealing section, and the last charge is 0.6 m away from the bottom of the hole to ensure that the blasting energy of the orifice and the bottom of the hole matches. In each scheme, the total length of explosive grain is 9.6 m, the length of single charge section is evenly distributed, and the length of air interval is equal, so as to avoid local energy concentration or vacancy. All explosive sections adopt simultaneous initiation mode to eliminate the interference of initiation sequence on blasting effect and focus on the influence of interval structure itself. Through the above scheme design, the axial distribution law of blasting energy under different interval numbers can be systematically compared.

3.3. Evolution characteristics of stress wave propagation

Explosion stress wave is the main power source of initial damage and crack initiation of rock mass, and its propagation and distribution characteristics directly determine the utilization efficiency of blasting energy. In deep hole pre-splitting blasting, the propagation and evolution of stress wave is the leading and dominant process of explosion energy transfer, initial damage of rock mass and crack initiation. The propagation and evolution characteristics of the stress wave directly determine the efficiency of the 'gas wedge effect' of the subsequent detonation gas and the forming quality of the pre-splitting surface. By extracting and comparing the effective stress (Von Mises Stress) nephograms of Scheme 1, Scheme 2 and Scheme 3 at different characteristic moments (t=120 μs,360 μs,720 μs,2000 μs) after the detonation of explosives, as shown in Fig.4-2, the propagation process of stress wave under the four schemes can be intuitively compared, and the regulation mechanism of interval charge structure on stress wave propagation path, energy distribution uniformity and action time can be revealed.



Option 1



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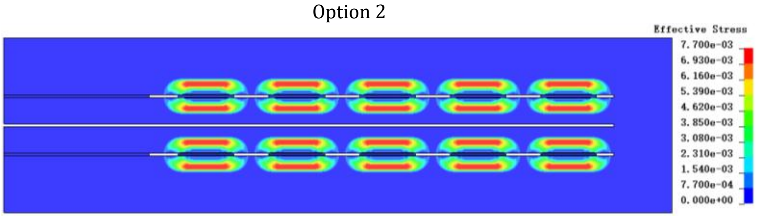
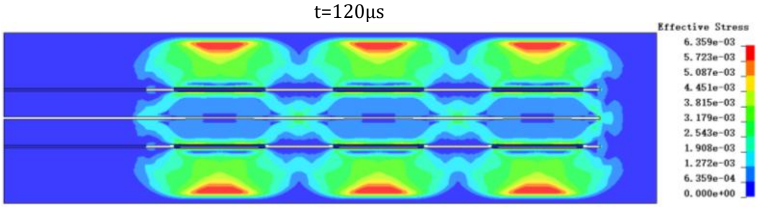


Option 3

t=120μs



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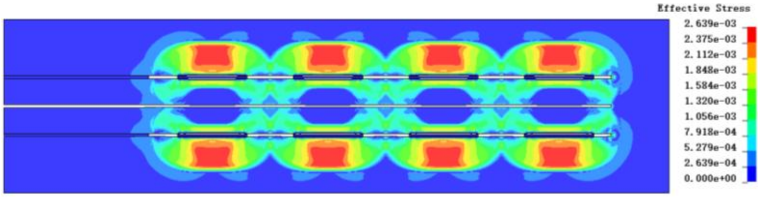

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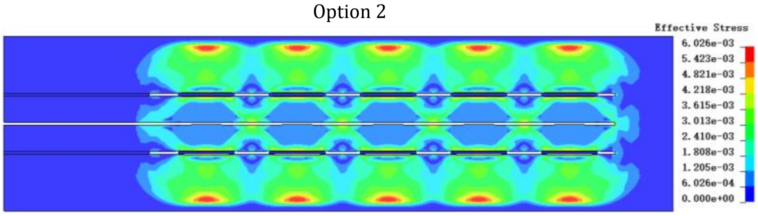
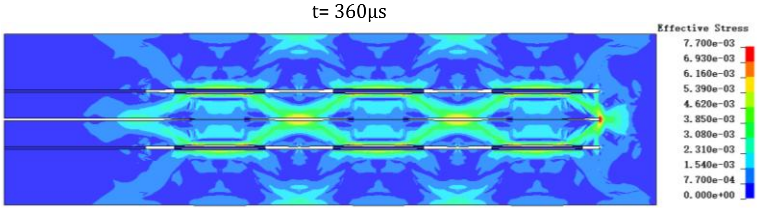
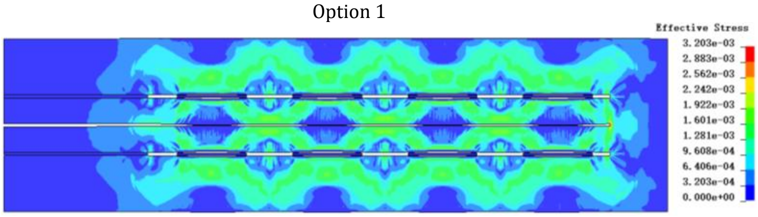


Option 3

t= 360μs



Option 1



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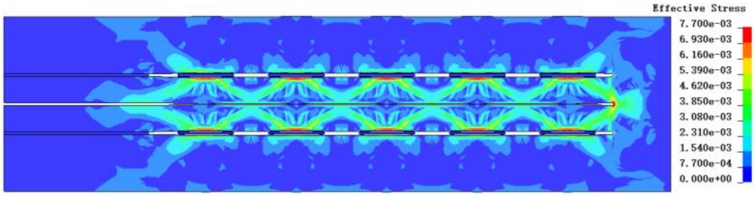
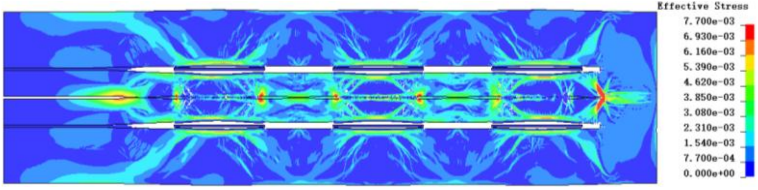
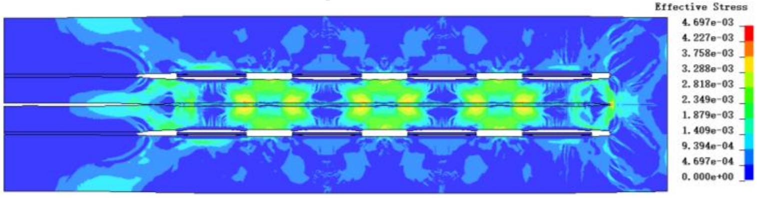


Option 3

（c）t=720μs



Option 1



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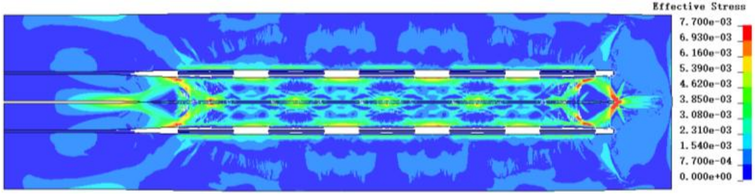


Option 3

（d）t=2000μs

Fig 2 Stress cloud diagrams of the blasting process under different schemes

In the initial initiation stage of t = 120 μs, the stress wave fronts of the three schemes all move forward in a regular columnar shape with the charge hole as the center, and the energy is highly concentrated around the charge hole. Scheme one has high concentration of stress wave energy, regular wave front shape but limited radial diffusion range ; in Scheme 2, the stress wave is more evenly distributed in the axial direction, and the wave front shows good synergistic propulsion characteristics. In Scheme 3, the energy of single charge is dispersed, and the initial strength of stress wave is low, but the synergistic effect of multiple charge segments makes the wave front distribute most evenly in the axial direction.

As time progresses to t = 360 μs, the stress wave propagates to the inter-hole region and begins to interact. The stress wave of the first scheme is mainly superimposed in the middle area of the longer charge section, forming a local high stress area. However, due to the uneven distribution of axial energy, the stress field has obvious ' saddle-shaped ' distribution characteristics at the junction of the charge section, that is, the stress in the middle of the charge section is high, while the stress in the corresponding area of the interval section is low. This discontinuous stress distribution may lead to the fluctuation or discontinuity of the pre-crack surface during the expansion process ; the stress wave of the second scheme produces multiple effective superposition in the axial direction, which makes the stress field distribution in the inter-hole area more continuous and stable. It is particularly noteworthy that the stress wave superposition effect around the guide hole has become significant, and obvious stress concentration has occurred, which creates favorable mechanical conditions for the subsequent use of the guide hole to guide the directional propagation of cracks ; scheme 3 forms a continuous stress band in the inter-hole area, but the weak superposition effect leads to the low peak value of stress wave and the overall stress wave intensity. The stress wave of Scheme 3 forms a continuous stress band in the inter-hole area. However, due to the weak energy of a single section, the strength of the overall stress field after stress superposition is relatively low, and the strength of the wave front is insufficient, which may affect the driving force of crack initiation and propagation.

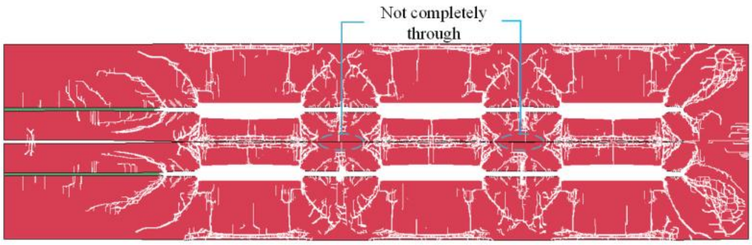
When t=720 μ s, the stress wave has completed multiple reflections and superposition in the inter-hole area, and its distribution characteristics are directly related to whether the pre-splitting surface can be connected with high quality. The ' saddle-shaped ' segmentation feature of the stress field in Scheme 1 still exists, indicating the inherent defects of its energy distribution. Although the stress concentration in the middle of the charge section is beneficial to local crushing, the low stress area in the interval section may become the weak link of the pre-splitting surface expansion, affecting its flatness and continuity. The stress field distribution of the second scheme is uniform and continuous, and the reflected tensile stress around the guide hole and the incident stress wave form a good superposition, forming a persistent tensile stress zone on the hole connection line. At the same time, the effective stress in the rock mass between the holes still maintains a high level, which provides a continuous and uniform power source for the full expansion and penetration of the pre-splitting surface. The multi-stage charge of the third scheme realizes the full superposition of the axial stress, and the stress concentration effect around the guide hole is also obvious, but the overall stress intensity is low and the effective stress band is narrow, which may limit the crack propagation speed and the final length.

In the later stage of t =2000 μ s, the quasi-static stress field is maintained. In the later stage of the explosion process, the dynamic stress wave has been attenuated, and the quasi-static explosion gas pressure field becomes dominant. In Scheme 1, due to the concentrated energy release and large loss in the early stage, the quasi-static stress field attenuates rapidly and the action time is relatively short. Scheme 2 has the longest stress field maintenance time. The uniform energy release provides a stable and lasting pressure environment for the detonation gas, which can continue to act on the cracked cracks, so that they can fully expand and form a flat pre-cracking surface, while protecting the integrity of the retained rock mass to the greatest extent. In Scheme 3, the energy is too dispersed, resulting in insufficient stress field strength and rapid attenuation, and the effect of ' gas wedge ' of quasi-static pressure may be poor.

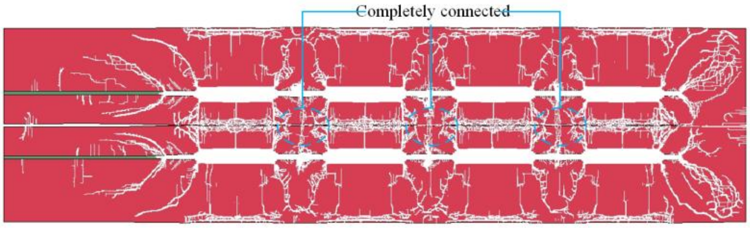
The comprehensive analysis shows that the second scheme performs best in the process of stress wave propagation. The optimal balance between the explosive energy intensity and the distribution uniformity is achieved : the local crushing caused by excessive energy concentration is avoided by sufficient interval number, and the sufficient energy intensity of single-stage charge is ensured, thus a continuous, uniform and persistent stress field is generated. In contrast, the energy distribution of Scheme 1 is uneven, and the overall energy intensity of Scheme 3 is insufficient.

3.4. Analysis of borehole surrounding rock crack after blasting

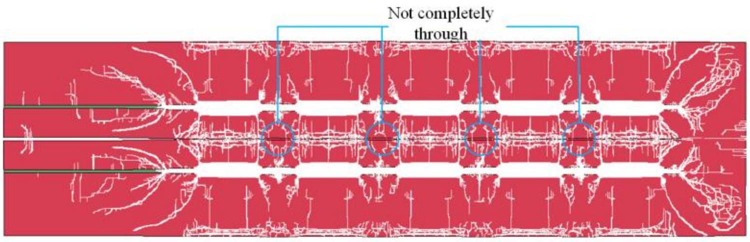
In order to quantitatively evaluate the influence of different interval charge structures on the damage characteristics of surrounding rock after blasting, based on the numerical simulation results, the final blasting effects of each scheme were systematically compared and analyzed from the crack morphology, focusing on the key indicators such as main crack length, penetration and pre-crack surface flatness, as shown in Fig.3.



Three-stage charge



Four-stage charge



Five-stage charge

Fig 3. Final blasting effects of each scheme

By extracting the crack characteristics of the three schemes at t = 2000 μ s, as shown in Table 2, the control effect of the number of intervals on crack propagation can be quantified.

Table 2. Crack characteristic parameters of each scheme

Option	Number of charge sections	Maximum length of the main crack (m)	Number of lateral branch cracks	Evaluation of the flatness of the pre-crack surface
Option 1	3	1.8	more	Wavy, partially non-through
Option 2	4	2.2	little	Flat and continuous with clear boundaries
Option 3	5	1.5	less	The discontinuous distribution cannot form an effective weak surface.

Scheme 1 adopts a three-stage charge structure, and the single-stage charge length is large, and the energy is concentrated in the axial distribution. The simulation results show that the average length of the main crack is 1.8 m, and the propagation is sufficient. The pre-crack surface shows obvious ' wavy ' undulation, and the crack propagation is rapid in the middle of the charge section, while in the corresponding area of the interval section between adjacent charge sections, the crack propagation is obviously lagging behind, forming a weak link that is not penetrated locally. This shape is not conducive to the formation of a continuous and flat weak surface required for engineering. Scheme 2 adopts a four-stage charge structure, the single-stage charge length is moderate, and the energy distribution is more balanced. The simulation results show that the average length of the main crack is 2.2 m, which is the highest among the three schemes, indicating that the energy utilization rate is the best. The pre-splitting surface is smooth and continuous, and the boundary is clear, which effectively avoids the excess or deficiency of local energy, so that the crack propagates uniformly and stably along the direction of the hole connection, forming a high-quality directional pre-splitting surface. Scheme 3 adopts 5-stage charge structure, the length of single-stage charge is the smallest, and the energy is too dispersed. The simulation results show that the average length of the main crack is only 1.5 m, and the propagation depth is seriously insufficient. The cracks are intermittently distributed, and the whole is broken rather than linearly connected. Although there are few lateral branch cracks, due to the lack of blasting driving energy, it cannot meet the engineering requirements of deep hole pre-splitting blasting.

Based on the analysis of crack morphology parameters, the four-stage interval charge structure of scheme two is the best in crack propagation length, penetration efficiency and pre-crack surface flatness. Its reasonable energy segmented release mode ensures that the main crack can expand quickly, fully and evenly, which is the best charge structure scheme to achieve high-quality deep hole pre-splitting blasting.

4. Conclusion

(1) The regulation mechanism of the interval charge structure on the explosion energy and pre-splitting crack formation is revealed. The interval charge divides the explosive into multiple segments through the axial interval medium, and realizes the regulation of the crack ' initiation-propagation-penetration ' process through the segmented release of the axial energy. By analyzing the three stages of rock mass initial crack initiation stage, crack directional expansion stage and pre-splitting surface penetration stage, the optimization of stress wave superposition and detonation gas action time by segmented release energy is explained, which promotes the formation of continuous and flat pre-splitting surface.

(2) The regulation law of interval charge structure on stress wave propagation and energy distribution is revealed. By comparing and analyzing the effective stress cloud diagrams of the three schemes, it is found that the number of intervals significantly affects the axial distribution uniformity of explosion energy. The four-stage charge has the best performance in the process of stress wave propagation, and the best balance between the intensity of explosion energy and the uniformity of distribution is achieved. It not only avoids the local high pressure caused by excessive energy concentration, but also avoids the insufficient overall strength caused by excessive energy dispersion, forming a continuous, uniform and lasting stress field, which provides a basis for the high-quality penetration of the pre-splitting surface.

(3) The four-stage charge forms a high-quality pre-cracking surface with smooth continuity and clear boundary. The average length of the main crack is 2.2 m, and the number of lateral branch cracks is small, which has the least disturbance to the surrounding rock. In contrast, in Scheme 1, the pre-cracking surface is wavy and partially unconnected due to uneven energy distribution. In Scheme 3, the cracks are intermittently distributed due to insufficient energy drive, and an effective weak surface cannot be formed.

Based on the quantitative comparison of crack shape parameters, damage range and energy transfer efficiency, the four-stage interval charge is the optimal charge structure for deep hole pre-splitting blasting. The structure ensures the full and uniform expansion of the main crack through a reasonable energy release mode, and effectively suppresses the lateral energy dissipation. The engineering goal of ' directional pre-splitting and minimum damage ' is achieved, which provides a theoretical basis for field engineering applications.

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