Experimental study and application of medium-length hole blasting technique in coal-rock roadway

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Abstract
In this study, mechanical mechanism analyses of hole cut blasting and in situ hole cut blasting tests using different cutting programs were conducted to investigate the hole cut blasting mechanism under the influence of complicated geological conditions and its blasting excavation effect. The hole cut blasting mechanism was evaluated under the background of medium-length hole cut blasting test in a typical coal-rock roadway in Xiayukou coal mine of Hancheng mining area in Western China to improve the blasting excavation efficiency in coal mine roadways. Test results indicated that the rock clamping action is remarkably enhanced when the depth of medium-length holes, which are impacted by various complicated geological factors, reaches more than 1.8 m under weak coal-rock mass conditions. At the same time, the antidrag effect is good when double-wedge cut blasting is selected, and its mitigation of rock clamping action is reflected through the reduction of rock resistance of phase I hole cut blasting. The enhanced blasting effect is embodied by the footage cycle and forming effect of blasting, and the footage cycle of single blasting increases from 1.6 to 2.0 m, thereby indicating its remarkable economic benefits. The results of this study can provide a reference for hole cut blasting design and mechanism study of weak coal-rock masses under complicated geological conditions.

KEYWORDS
coal-rock roadway, double-wedge cut, medium-length hole blasting

1 INTRODUCTION

The exploration of weak thin seam mining under complicated conditions is of great importance to satisfy the increasing demand of energy supply and continuous exhaustion of coal resources in China. With the increasing coal demand, new requirements have been proposed for coal mine roadway excavation efficiency under complicated conditions. Roadways are mainly located on the coal-rock environment under thin seam mining conditions, and blasting excavation is widely adopted in these roadways. The footage cycle of ordinary shallow hole blasting is low, leading to slow excavation progress and continuous tension in the advancement of working faces and cannot satisfy the high productivity demand of coal mines. Therefore, the hole cut blasting mechanism of coal-rock masses under different conditions should be investigated to provide a theoretical basis for efficient roadway hole cut blasting design.
Blasting method plays a dominant role in roadway excavation of coal mines in China. However, blasting efficiency of rock roadway has remained at a low level, only 70 m/month, and on the basis of the current equipment and technology of the hole cutting, the excavation speed is improved only by the design of the hole cutting. The method of hole cutting is to use the drilling and blasting to excavate the underground space. When blasting, several blasting holes are first detonated, which can create more free surfaces for other holes, thus improving the overall blasting effect. Existing cutting modes mainly include parallel cutting, wedge cutting, and mixed cutting designed according to different geological conditions of the mine. Parallel cutting is mainly single-free-face blasting, where blasting holes are perpendicular to free face. The blasting effect is favorable when the depth of blasting holes is as small as 1.6 to 1.8 m, although it is obviously impacted under the depth condition of medium-length holes. Wedge cutting features broad free face and good blasting effect. The layout of cut holes is influenced by roadway cross-sectional size, making it only applicable to shallow hole blasting. When the medium-length hole blasting of 1.8 to 2.5 m is carried out, the existing hole cut blasting methods have poor applicability to roadway blasting excavation of coal mines with complicated geological conditions. Therefore, it is important to study the blasting mechanism of the medium and deep hole cutting under different conditions and improve the efficiency of blasting.

Numerous scholars have conducted multi-aspect studies focusing on hole cut blasting mechanism to improve the hole cut blasting efficiency of roadways. They have proposed various hole cut blasting techniques for coal mine roadways based on the selection of hole cut blasting method, depth of blasting holes, and hole spacing. The designed hole cut blasting methods, such as double-wedge and quasi-parallel cutting, have achieved satisfying results in roadway blasting tests of coal mines. The existing studies have mainly focused on cut blasting mechanism of hard rock roadways with simple geological conditions. In reality, many complicated factors should be considered because of the complicated fracture structure of weak coal-rock masses. The cut blasting mechanism studies under this condition remain in a standstill phase, where cut blasting design lacks a reasonable basis.

Many scholars have conducted numerous studies on the cut blasting mechanism of coal mine roadways and proposed several cutting techniques to weaken the rock clamping effect under all kinds of complicated geological conditions and improve the hole cut blasting quality of coal-rock masses. Sainoki et al. used traditional and substitutive numerical simulation methods to construct a 3D mathematical model of a single-blasting hole and comparatively analyzed the stresses and blasting efficiencies of different numerical methods. The results indicated that the substituted modeling method had higher accuracy in simulating the destruction area for each blasting hole. Yang et al. investigated the adjacent hole effect in blasting through theoretical analysis and numerical simulation. The results indicated that the tangential stress of blasting stress waves extended to adjacent hole wall was constantly greater than the radial stress. Cho et al. performed numerical simulation to evaluate the dynamic fracture process of bench-top blasting rocks, and the results manifested that the optimal crushing effect regarding blasting delay time depended on the pressure of blasting sound source, which was largely caused by stress waves and penetrated cracks. Drover et al. conducted a theoretical analysis of the shear mechanism of rock failure, presented the concept of symmetric pressure-relief charging blasting, and used a mixed stress blasting model to perform a numerical simulation of blasting design for providing a basis for blasting design parameters. Gao et al. conducted numerical simulation to assess the blasting influence mechanism at the drilling position. The results showed that the initial position played a significant role in the blasting energy distribution transferred to surrounding rocks. Babanouri et al. performed numerical simulation to investigate the fractured rock masses caused by single-hole blasting in an iron mine and their mechanical properties, and the results indicated that the high-furnace blasting simulated through linear superposition fitted well with the actual conditions. Graaf et al. utilized a review methodology to introduce the application of all kinds of current drilling and blasting techniques for reducing the rock failure and loosening phenomenon beyond the blasting excavation line to the minimum using all kinds of techniques. The results showed that the constraint degree of explosive energy close to the slope played a vital role in the generated wall failure. Sim et al. evaluated the crushing caused by atmospheric pressure during rock blasting using multiple equal-length radial crack models, indicated that the stress intensity factor of cracks reduced with the crack extension from blasting holes, and confirmed the crack length. The above-mentioned studies have focused on the hole cut blasting mechanism without considering the influence of coal- rock lithology under complicated geological conditions. The hole cut blasting mechanism of coal-rock masses under the influence of various factors should be investigated from the propagation direction of mesoblasting cracks using different hole cutting techniques.

Numerous scholars have investigated the crack propagation mechanism in rock hole cut blasting to evaluate the blasting mechanism of coal-rock masses under the influence of all kinds of conditions and determine the influence of different hole cutting techniques on hole cut blasting crack propagation. Su et al. used stress wave theory to analyze the propagation laws of rock blasting stress wave and crack propagation laws triggered by the propagation of stress wave, and the results indicated that the original cracks in the coal mass had a great impact on the propagation direction of secondary and primary cracks. Yoshiaki et al. used a small-scale
blasting test to evaluate the strain curve on the surface of postblasting mortar building block and indicated that the strain rate of blasting surrounding rocks had a great impact on the generation and propagation of cracks. Salmi et al.\textsuperscript{14} used thick-walled cylinder theory and numerical method to analyze the presplitting blasting mechanism of adjacent blasting holes, and the results showed that the collision between two adjacent stress waves generated tension waves that played a crucial role in presplitting. Fakhimi et al.\textsuperscript{15} used fluid dynamics to investigate the interaction of blasting-induced gas and cut holes, and the results indicated that the gas-rock interaction generated a series of continuous compression waves in the rock specimens, and radial cracks propagated under the continuous action of compression waves and crack tips. Far et al.\textsuperscript{16} used Monte Carlo method to calculate the crushing region radius under the effect of blasting waves that exceeded the required probability value, and the results showed that the exceeding probability of crack propagation sharply dropped with the increase in crushing region radius.

Most of the above-mentioned studies have focused on the blasting mechanism of coal-rock masses from the aspect of blasting crack propagation. These studies have demonstrated the influence of blasting crack propagation on the blasting effect, and few studies have investigated the blasting mechanism under the influence of multiple complicated factors. Rainai\textsuperscript{17} evaluated the fracture mechanical behavior of rocks under dynamic loading condition through a small-scale blasting test and indicated that the rock stiffness would influence its dynamic fracture. On the basis, Du et al.\textsuperscript{18,19} used a similar method to study the failure behavior of different rock types (granite, red sandstone, and cement mortar). Saiang et al.\textsuperscript{20} conducted numerical simulation to investigate the influences of strength and stiffness of blasting destruction area on blasting-induced rock damage, and the results showed that blasting stress and geological conditions inside the near-field rocks were anisotropic, and the destruction area caused by blasting influenced the boundary stress. Goodarzi et al.\textsuperscript{21} used the finite element method to conduct an analog computation of stress intensity factors of crack media, and the results manifested that the final crack length caused by blasting was mainly determined by atmospheric pressure rather than the initial crack length generated by stress wave. Zhu et al.\textsuperscript{22} used a stress-concentrated cylindrical rock blasting model to assess the influencing conditions in actual blasting and indicated that factors, such as coupling media, constraint conditions, boundary conditions, and detonating position of explosives, would generate important influences on rock crushing under the effect of dynamic load. Wang et al.\textsuperscript{23,24} used the Harries mathematical model to optimize the MDO algorithm and conducted industrial experiments in China's fankou lead-zinc mine. The results show that the MOD algorithm can improve the rock blasting effect of deep hole blasting and improve energy utilization. Thus, the blasting mechanism and blasting effect under the influence of all kinds of complicated factors should be investigated.

The advantages and disadvantages of the existing blasting forms in hole cut blasting were analyzed under the background of medium-length hole cut blasting tests in a typical coal-rock roadway in Xiayukou coal mine of Hancheng mining area in Western China to address the limitations. Medium-length hole double-wedge cutting that could satisfy the blasting efficiency was designed. Theoretical analysis was conducted to investigate the mechanical mechanism of double-wedge hole cut blasting, followed by an experimental study of medium-length hole cut blasting in a weak coal-rock roadway under parallel cut, wedge cut, and double-wedge cut forms to provide reference for cut hole blasting design and blasting mechanical study of weak coal-rock masses under complicated geological conditions.

In this study, theoretical analysis and industrial test were conducted to analyze the cut blasting mechanism under weak coal-rock conditions to provide reference for cut blasting design of coal mine roadways under complicated conditions.

## 2 ANALYSIS OF HOLE CUTTING

The rocks at the bottom of deep blasting holes in the roadway are constantly difficult to crush because of the influence of all kinds of complicated factors, and the blast sockets, which are 2-4 times larger than the original hole diameter, remain after blasting. Explosive payload was usually increased in the past to improve the blasting effect, but it was accompanied by problems of decreased safety and blasting efficiency. The hole cut blasting design lacks a reasonable basis when the selected hole cut form does not match the geological conditions well, leading to partially low blasting efficiency. Therefore, the improvement of roadway blasting efficiency depends on designing a medium-length hole cut blasting mode that well matches the geological conditions.

### 2.1 Optimization of hole cut mode

Hole cut modes in roadway excavation are mainly divided into two major types, namely wedge and parallel cut, which have their own features with different scopes of application.

As shown in Figure 1, the blasting hole depth in parallel cut is not limited by the roadway section, the rock-throwing distance is small after blasting, and blast heaps are relatively concentrated, which have a minor influence on the equipment and can easily realize parallel operation of multiple rock drills. The implementation and design of parallel cut are complicated with high requirements for blasting parameter design and construction level, hole position and depth, and blocking airtightness. The hole cut blasting quality degrades
when the rocks at the deep part of the blasting hole bottom cannot be effectively ejected.

Wedge cut mode has good adaptability and can achieve satisfying hole cut effect under any lithological condition by effectively throwing rocks in the cavity, as shown in Figure 2. The formed cavity has large volume and broad free face after hole cut blasting that can create beneficial blasting conditions in subsequent hole blasting processes. The cut hole position, layout of blasting holes, and dip angle precision have minor influences on hole cut blasting effect. The implementation process can be easily manipulated by the worker, although the depth of cut holes is limited by roadway sectional size, making it a disadvantage.

Medium-length hole double-wedge cut was designed based on the analysis of advantages and disadvantages of parallel and wedge cutting to improve the single-blasting footage cycle of weak coal-rock roadway, as shown in Figure 3. On the blasting excavation face, a proper position was selected and arranged with a small quantity of shallow blasting holes prioritizing detonation when blasting starts, a cavity with small volume was formed, and a large free face was created for subsequent hole blasting. Blasting holes that were first detonated first were phase I cut holes. Outside these blasting holes, another circle of blasting holes was arranged within a certain interval and detonated slightly different from phase I cut holes. The cracks formed in phase II cut blasting ran through those formed in phase I cut blasting based on the large free face created in phase I hole cut blasting, thereby forming a large cut cavity that could effectively elevate the blasting footage cycle and guarantee the blasting effect.

As shown in the cut blasting process under different cut modes in Figures 1-3, the depth of parallel cut blasting holes was large. The forming effect of roadway blasting was poor, whereas that of wedge cut blasting was good with shallow blasting holes although it could not guarantee the improvement of footage cycle. Double-wedge cut possesses the advantages of parallel and wedge cutting because it could ensure that the blasting depth in the cut blasting cavity to reach the depth standard of parallel cut blasting for the sake of cut blasting under medium-length holes and realize good forming effect of wedge cut blasting in the roadway.

In soft rock, the cutting is different from the medium hard rock. The soft rock joint fissure development, water swelling and poor stability, the weakening effect on the explosive energy is more obvious. It is unscientific to increase the explosive size by increasing the explosive amount. The key point in improving the blasting efficiency is still to design the grooving method under the deep hole. Combining the advantages of parallel and wedge cutting, the above-mentioned complex wedge cutting is designed, and the blasting efficiency can be effectively improved by adjusting the blasting parameters according to the soft rock conditions. The double-wedge cut mode had incomparable effects to other cut modes when promoting rock blasting through the above analysis of cut blasting of coal-rock mass. Thus, the analysis of mechanical mechanism of double-wedge cut blasting was conducted to verify the scientificity of this cut mode under medium-length holes.
Explosives have dynamic and static effects in blasting. The static effect is obvious during blasting because of the properties of permitted explosives and geomechanical properties of coal mine. Thus, the static effect of detonation gases was mainly utilized to analyze double-wedge cut blasting.

The 3D model map of double-wedge cutting is shown in Figure 4. Assuming that the static effect of detonation gases under the blasting action causing the crushing between cavity and surrounding rocks, namely LMNO face of phase I cut hole, was firstly detonated, a cavity was formed through cut blasting as the free face of blasting of the next phase, and rock blasting in the cavity mainly bored shear and tensile failures. ABFE, DCGH, ADHE, and BCGF faces experienced static shear failure, whereas EFGH face underwent tensile failure when phase II cut holes were detonated. The rocks in phase I cut volume did not require work because of the influence of the middle free face. As shown in Figure 5, most of the energy was used to crush and throw rocks, the clamping resistance of the rocks themselves reduced, and phase II cut blasting was effective.

where $F_2$ is the cavity-forming power in phase II hole cut, $F_1$ is the cavity-forming power in phase I pilot cut blasting, $F_r$ is the resistance borne by rock cavity I in direct wedge blasting, $Q_S$ is the cavity-forming frictional resistance in rock hole cutting in the direction of the least resistance line, $Q$ is the total cavity-forming frictional resistance in rock hole cutting, and $\sigma_2$ is the normal stress on the face, $\sigma_2 = \frac{\mu}{1-\mu}\sigma_1 = \frac{\mu}{1-\mu}\gamma z$, where $\sigma_1$ is the shear stress on this face, $\gamma$ is the rock volume weight, and is distance from this face to the ground surface.

The following condition should be satisfied for rocks in the entire cavity to be effectively ejected and reach the limit equilibrium under the static effect of detonation gases, which is expressed as follows:

$$F_1 + F_2 \geq Q_{s} + F_r$$  \hspace{1cm} (1)

The cavity-forming power in cut blasting is basically fixed, and the cut blasting effect is related to rock clamping resistance of this cut mode when the design cut angle and explosive payload are fixed.

1. **Shear resistance of lateral rocks**
   Frictional resistance under the shear action of lateral rocks is closely related to the rock properties and volume of cut cavity, and frictional resistance of each face in the cut cavity in Figure 4 can be calculated as:

   $$Q_S = Q_{ADHE} + Q_{BCGF} + (Q_{ABFE} + Q_{DCGH}) \sin \alpha$$  \hspace{1cm} (2a)

   $$Q_{ABFE} = (c + \sigma_2 \tan \varphi)2aL$$  \hspace{1cm} (2b)

   $$Q_{ADHE} = (c + \sigma_1 \tan \varphi)(b + B)L \sin \alpha$$  \hspace{1cm} (2c)

   where $c$ is the cohesion, and $\varphi$ is the internal friction angle.

2. **Rock resistance in phase I cut blasting**
   The stress-bearing mode of rocks in phase I cut blasting was basically identical with that of rocks in phase II of double-wedge cut blasting, as shown in Figure 6. The cut blasting rock mass mainly experienced clamping resistance $F_r$ of the rock itself and frictional resistance $Q_s$. The bottom of the...
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blasting hole bored the resistance caused by the stretching effect, which was in reverse direction to detonation.

Therefore, total resistance $F$ of phase I wedge cut blasting, namely the resistance that can be reduced in phase II cut blasting is expressed as:

$$ F = F_i = F_p = \frac{M}{2D} \lambda_m V_p^2 + 2af \sigma_t $$

The phase I pilot wedge cut blasting effectively ejected the rocks inside the rock mass in phase I and reduced the rock-throwing resistance under medium-length holes in phase II double-wedge cut blasting when creating a free face for cut blasting in the next phase, indicating that this cut blasting mode effectively reduced the rock clamping resistance. Under this cut mode, the depth of blasting holes elevated, and medium-length hole cut blasting was reasonable and feasible.

2.3 Reasonable selection of the depth of medium-length holes

The depth of blasting holes has a direct impact on the completion status of various working procedures in one cycle and blasting excavation footage and blasting effect. Reasonable depth of blasting holes should adapt to the roadway excavation and support mode, that is, the excavation and support length should match the footage cycle in each blasting process. In double-wedge cut, the depth of blasting holes, namely phase II cut depth, should match with the excavation and support length of the mine and is influenced by phase I cut depth. The more the rocks blasted in phase I cut blasting are, the larger the formed free face, and the smaller the rock clamping resistance will be when the depth of blasting holes is elevated for medium-length hole cut blasting in phase II.

The depth of blasting holes in phase I cut blasting had a proportional relation with that in Phase II cut blasting, where depth in phase II cut blasting could be determined on the basis of rock drill, circulation mode, excavation and support operation mode, rock conditions, and explosive level. The depth of blasting holes in phase II cut blasting was related to the design of blasting parameters of blasting holes because of limitation of the depth of blasting holes in phase II cut blasting and roadway section.

Figure 7 shows the layout plan of cut blasting holes in double-wedge cut blasting, where hole bottom distance $f$ of phase I cut holes can be jointly determined through radius $R_1$ of crushing zone and attention coefficient $e$ of shock wave:

$$ e = 2^{(1+\varepsilon)/\varepsilon} R_1 $$

Hole bottom distance $f$ of phase II blasting holes is associated with radius $R_2$ of the crack zone of blasting holes. The bottom of phase II cut holes should run through the central crack zone, and the formula is expressed as:

$$ R_2 \leq f \leq 2R_2 $$

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On the basis of the determined hole bottom spacing, port-hole spacing can be determined through the depth of arranged blasting holes as:

\[ S_1 = e + 2h / \tan \beta \] (6)

\[ S_2 = f + 2H / \tan \beta \] (7)

Vertical depth \( h \) of blasting holes arranged in wedge cut blasting is certain, but the double-wedge cut mode can acquire large footage cycle \( H \) based on the change of cut mode when the roadway sectional area is fixed, and the difference value is calculated as:

\[ H - h = \left[ (S_2 - S_1) - (f - e) \right] \tan \beta / 2 \] (8)

The depth of phase II cut blasting hole is as follows:

\[ L = \frac{H}{\tan \beta} = \frac{\left[ (S_2 - S_1) - (f - e) \right]}{2} + \frac{h}{\tan \beta} \] (9)

The selection criteria for the depth of blasting holes under this cut mode and double-wedge cut blasting parameters were introduced through the static analysis of the medium-length hole double-wedge cut blasting mechanism to provide a powerful theoretical support for medium-length hole roadway blasting test in weak coal-rock roadways.

3 | RESULT ANALYSIS AND DISCUSSION

3.1 | Test conditions

The test working face used was the mining roadway of 23 210 working face, which was a coal-rock roadway of Xiayukou coal mine in Hancheng mining area.

The test mining roadway on 23 210 working face was located at +300 m level, with mountain-covering thickness of approximately 500 m, and a local false roof of mudstone with 0.1 m. The coal seam was approximately 1.0 m on average with low strength, and the overlying strata featured falling during excavation. The roadway section of this weak coal-rock roadway was rectangular with a sectional area of 13.8 m², and the excavation was accompanied by roof and floor bursting, its roof was mainly mudstones \((f = 2-3)\), and its floor was mostly fine sandstones \((f = 3-5)\). The schematic of the coal roadway is shown in Figure 8.

3.2 | Test program design

For the blasting difficulty existing in weak coal-rock roadways, double-wedge cut blasting mode was utilized to optimize the arrangement of blasting holes. Medium-length hole blasting was used in the design to increase the depth of blasting holes because of its ability to improve the roadway blasting excavation effect. To explore the influence of cut blasting mode on the blasting excavation efficiency of weak coal-rock roadway, three blasting programs were designed for the test by changing the layout of cut holes, arrangement form of blasting holes, and depth of blasting holes.

3.2.1 | Hole cut mode

On-site rocks were weak No. 2 coal seam, mudstone, and fine sandstone. Three hole cut modes, namely parallel, ordinary wedge, and double-wedge cut, were designed in the test.

Parallel cut mode: cut hole spacing \( L_1 = 300 \) mm, auxiliary hole spacing \( L_2 = 540 \) mm, and periphery hole spacing \( L_3 = 600 \) mm;

Ordinary wedge cut mode: porthole spacing of cut holes \( L_1 = 1400 \) mm, hole bottom spacing \( L_2 = 300 \) mm, angle of inclination \( \alpha = 73^\circ \), auxiliary hole spacing \( L_3 = 400 \) mm, and periphery hole spacing \( L_4 = 500 \) mm.

Double-wedge cut mode: porthole spacing in phase I cut \( L_1 = 550 \) mm, hole bottom spacing \( L_2 = 200 \) mm, port-hole spacing in phase II cut holes \( L_3 = 1680 \) mm, auxiliary...
hole spacing $L_5 = 550$ mm, and periphery hole spacing $L_6 = 550$ mm.

The three cut blasting programs were designed and tested in the coal-rock roadway. The optimal layout form of weak coal-rock mass was determined through the actual blasting excavation footage.

### 3.2.2 | Blasting parameters

The explosive consumption of a single cut blasting hole in the three blasting programs was determined in terms of blocking length and test safety, as shown in Table 1.

| Explosive consumption/kg | Program I | Program II | Program III |
|--------------------------|-----------|------------|-------------|
| Explosive consumption per unit area | 0.7 | 0.8 | 0.8 |
| Explosive consumption of a single blasthole | 0.9 | 1.2 | 1.2 |

Number (N) of blasting holes can be determined using a blasting hole equipartitioning method of circulating explosive quantity and is calculated as $N = 48$.

The auxiliary holes and periphery holes and the number of blasting holes under the three blasting programs were determined to be 41, 48, and 44, respectively, on the basis of roadway sectional form combined with the arrangement principles of cut blasting holes.

Depth $L$ of blasting holes was calculated on the basis of excavation circulation time and support technology, where the row spacing of supporting anchor rods was $1.0 \text{ m} \times 0.8 \text{ m}$, and two-excavation and one-support mode originally adopted footage cycle of $1.6 \text{ m}$. Footage was increased to satisfy the

**FIGURE 9** Layout of blasting holes in program I. (A) Main view; (B) Left view; (C) Top view
demand of working face continuity, and row spacing of supporting anchor rods was adjusted to 1.0 m × 1.0 m. Footage cycle reached 2.0 m when two-excavation and one-support was adopted. Depths L of blasting holes under the three blasting programs were 2.4, 1.8, and 2.5 m, respectively, by considering the factors, such as wedge layout and roadway section.

### Table 2 Blasting design parameters in program I

| Name of holes       | Hole type | Hole depth/m | Hole distance/m | Angle(°) | Hole number | Loading capacity/kg | Blasting sequence |
|---------------------|-----------|--------------|-----------------|----------|-------------|--------------------|-------------------|
| Empty holes         | /         | 2.0          | —               | 90       | 90          | 1                  | I/II              |
| Cut holes           | 1-4       | 2.4          | 0.30            | 90       | 90          | 4                  | 1.5/6.0           |
| Auxiliary holes (1st circle) | 5-11     | 2.2          | 0.54            | 90       | 90          | 7                  | 0.9/6.3           |
| Auxiliary holes (2nd circle) | 12-19    | 2.2          | 0.33            | 90       | 90          | 8                  | 1.2/4.8           |
| Rib holes           | 20-25     | 2.2          | 600             | 88       | 90          | 6                  | 0.3/1.8           |
| Top holes           | 26-33     | 2.2          | 600             | 90       | 90          | 8                  | 0.3/2.4           |
| Bottom holes        | 34-41     | 2.2          | 600             | 88       | 90          | 8                  | 0.9/7.2           |
| Total               |           |              |                 |          |             | 42                 | 28.5              |

### 3.2.3 Layout of blasting holes

The layout of blasting holes and blasting design parameters in program I are shown in Figure 9 and Table 2, respectively. Layout features of blasting holes in program I: the cut holes were located at the middle and lower parts of the roadway, cut holes 1-4 and two circles of auxiliary holes 5-11.
and 12-15 were designed, and the detonation sequence was arranged as cut blasting holes (Ⅰ/Ⅱ), first circle of auxiliary holes (Ⅲ), second circle of auxiliary holes (Ⅳ), periphery holes (Ⅴ), and bottom holes (Ⅵ).

The layout of blasting holes and blasting design parameters in program Ⅱ are shown in Figure 10 and Table 3, respectively.

**TABLE 3**  Blasting design parameters in program Ⅱ

| Name of holes      | Hole type | Hole depth/m | Hole distance/m | Angle/(°) | Hole number | Loading capacity/kg | Blasting sequence |
|--------------------|-----------|--------------|-----------------|-----------|-------------|--------------------|------------------|
| Cut holes 1-4      |           | 1.6          | 0.30            | 73        | 90          | 4                  | 0.90             | 3.60             | I                |
| Cut holes 5-11      |           | 1.6          | 0.40            | 90        | 90          | 18                 | 0.60             | 10.80            | II               |
| Cut holes 20-25     |           | 1.6          | 0.50            | 79        | 90          | 8                  | 0.30             | 2.40             | III              |
| Cut holes 26-33     |           | 1.6          | 0.50            | 90        | 85          | 9                  | 0.30             | 2.70             | IV               |
| Cut holes 34-41     |           | 1.6          | 0.50            | 90        | 85          | 9                  | 0.45             | 4.05             | V                |
| Total              |           |              |                 |           |             | 48                 | 23.55            |                  |

Layout features of blasting holes in program Ⅱ: the cut holes were located at the middle of the roadway, cut blasting holes 1-4 and auxiliary holes 5-22 were designed, and the detonation sequence was arranged as cut holes (Ⅰ), auxiliary holes (Ⅱ), periphery holes (Ⅲ/Ⅳ), and bottom holes (Ⅴ).

**FIGURE 11**  Layout of blasting holes in program Ⅲ. (A) Main view; (B) Left view; (C) Top view
The layout of blasting holes and blasting design parameters in program III are shown in Figure 11 and Table 4, respectively.

Layout features of blasting holes in program III: the cut holes were located at the middle and lower parts of the roadway, phase I cut holes 1-2, phase II cut holes 3-6, and auxiliary holes 7-18 were designed, and the detonation sequence was arranged as phase I cut holes (Ⅰ), phase II cut holes (Ⅱ), auxiliary holes (Ⅲ), periphery holes (Ⅳ), and bottom holes (Ⅴ).

3.3 | Blasting effect analysis

The blasting effects of the three test programs are shown in Table 5.

The statistical results of blasting excavation effects under different cut modes in the industrial test are shown in Table 6. The following conditions were obtained through the analysis of evaluation indicators, such as excavation footage, blasting forming effect, and utilization efficiency of blasting holes:

1. In the test of the three blasting programs, double-wedge cut featured no residual holes, good roadway forming effect, and high single-time footage cycle that reached 2.0 m. The new technique of pilot wedge cut blasting in phase I was used. Thus, double-wedge cut had the advantages of wedge and parallel cutting, that is, good forming effect and large depth of blasting holes, thereby ensuring satisfactory hole cut effect.

| TABLE 4 | Blasting design parameters in program III |
|---------|----------------------------------|
| Name of holes | Hole type | Hole depth/m | Hole distance/m | Angle/(°) | Hole number | Loading capacity/kg |
| Cut holes (Phase I) | 1-2 | 1.5 | 0.55 | 73 | 90 | 2 | 0.6 | I |
| Cut holes (Phase II) | 3-6 | 2.5 | 0.84 | 73 | 90 | 4 | 1.2 | 4.8 | II |
| Auxiliary holes | 7-18 | 2.2 | 0.55 | 90 | 90 | 12 | 0.9 | 10.8 | III |
| Rib holes | 19-26 | 2.2 | 0.55 | 88 | 90 | 8 | 0.3 | 4.8 | IV |
| Top holes | 27-35 | 2.2 | 0.60 | 88 | 90 | 9 | 0.3 | 5.4 |
| Bottom holes | 36-44 | 2.2 | 0.55 | 88 | 90 | 9 | 0.6 | 8.1 | V |
| Total | | | | | | | 44 | 35.1 |

| TABLE 5 | Blasting effects of the 3 test programs |
|---------|----------------------------------|
| Program | Drilling depth/m | Footage/m | Residual hole depth/m | Layout of cut hole | Blasting forming effect |
| Cut holes | Auxiliary holes | Periphery holes | Footage/m | Bottom | Broken block | Roadway formation |
| Program I | 2.4 | 2.2 | 2.2 | 2.0 | 0.20-0.30 | Parallel | Yes | Large block | Poor |
| Program II | 1.8 | 1.6 | 1.6 | 1.6 | 0.10-0.20 | Wedge | No | Small block | Good |
| Program III | 2.5/1.5 | 2.2 | 2.2 | 2.0 | 0.05-0.20 | Double-wedge | No | Small and uniform block | Good |

| TABLE 6 | The blasting effect of the test |
|---------|--------------------------------|
| Program | Cut modes | Single circulation footage/m | Blasthole utilization/% | Monthly footage (m/month) | Detonator consumption (a detonator/m⁻³) | Unit consumption of explosives (kg · m⁻³) | Excavation situation |
| Program I | Parallel cut | 2.0 | — | 80 | 1.71 | 1.28 | Underexcavation is serious |
| Program II | Wedge cut | 1.6 | 81.1 | 80 | 2.31 | 2.02 | Many residual marks and slow progress |
| Program III | Double-wedge cut | 2.0 | 86.9 | 120 | 1.89 | 1.61 | Good blasting effect |
2. The test of the three blasting programs indicated that this kind of double-wedge cut was totally suitable for medium-length hole blasting with utilization efficiency of blasting holes reaching 86.9% compared with parallel and wedge cutting.

3. The test indicated that the rick resistance borne by the optimized cavity-forming process of double-wedge cut blasting obviously reduced, in which single-time footage cycle reached 2.0 m, roadway forming effect was good, and the obtained double-wedge cut blasting effect was basically identical with that through theoretical analysis, manifesting that the blasting parameters under this cut mode were reasonably calculated.

The change laws of rock clamping effect under different cut modes with the increasing depth of blasting holes were obtained through the cut blasting test of the weak coal-rock roadway, as shown in Figure 12.

4 | CONCLUSIONS

The rock clamping resistance overcome by double-wedge cut blasting was investigated through the mechanical mechanism analysis of cut blasting using the existing cut blasting mechanisms to determine the cut blasting mechanism under weak coal-rock conditions. The resistance reduction and efficiency improvement effects of double-wedge cut blasting were verified through the medium-length hole cut blasting test under weak coal-rock conditions, and the main conclusions were obtained as follows:

1. For double-wedge cut, the traditional wedge cut was designed into one-deep-hole and one-shallow-hole-phased detonation. The cavity-forming effect in phase II deep hole cut blasting was remarkable on the basis of the large free face created in phase I shallow hole cut blasting.

2. The overcome rock clamping effect was mainly embodied by pilot blasting in phase I, thereby avoiding the clamping resistance of cut blasting rocks in shallow holes under direct deep hole blasting conditions.

3. Combined with the cut blasting effects under different cut modes and depths of blasting holes in the test, the rock clamping resistance obviously enhanced when the depth of blasting holes was higher than 1.8 m under weak coal-rock conditions.

4. The rock breaking mechanism of medium-length hole cut blasting under weak coal-rock conditions was obtained based on the test results. The test results and mechanical mechanism analysis showed that the designed double-wedge cut mode had good blasting effect, making it applicable to high-efficiency cut blasting under all kinds of complicated geological conditions.

The proposed rock breaking mechanism of medium-length hole cut blasting under weak coal-rock conditions was scientific and reasonable. The double-wedge cut blasting mode based on the proposed mechanism had strong “resistance reduction and efficiency improvement effects,” thereby providing a reference for future analysis of coal-rock blasting mechanism under all kinds of complicated geological conditions. The applicability of cut blasting mechanism under different lithological conditions may be relatively different because this study only focused on the medium-length hole cut blasting mechanism under weak coal-rock conditions, leading to a certain deviation of actual cut blasting efficiency. Therefore, the cut blasting mechanism analysis under various lithological conditions should be conducted in future studies, and laboratory-scale study of cut blasting crack propagation should be introduced to contribute to the recognition of coal-rock cut blasting mechanism under different influencing factors.

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