Experimental Study on The Effect of Charge Structure of Blasting on Damage to Dirt Band in Thin Coal Seam

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Abstract. Based on the coalmines with thin coal seam containing hard dirt band in Shandong Province, aiming at the problem of difficult mining caused by hard dirt band in the process of thin coal seam mining, the damage to hard dirt band by blasting in different charge structures was studied. According to the propagation law of blasting stress wave in coal and dirt band in different charge structures, an experimental platform was set up, and the damage characteristics of dirt band by blasting stress wave under the action of ordinary charge blasting and shaped charge blasting were studied through similar simulated comparative tests. The results show that in the ordinary blasting, the cracks spread out disorderly along the radial direction of the blasting hole and the damage of the dirt band is not so good; however, in shaped charge blasting, the peak stress increases 1.32 times in the direction of energy accumulation, while decreases 22% in the direction of non-energy accumulation, making the explosive energy more concentrated in the dirt band and forming a long and wide directional main crack in the dirt band.

1. Introduction

According to the statistics, thin seam reservoirs are relatively abundant in China. In state-owned key coalmines, the recoverable thin seam reserves can account for 17% of the total recoverable coal reserves, but the output is less than 10% of the total coal production. The main reason is that the hard dirt band in thin seam restricts the mechanized mining of working face. Taking Shandong Province as an example, the main occurrence of coal are thin seams, in which the thin seams containing hard dirt bands account for about 53% [1]. Therefore, effective treatment of dirt band in coal seam is the key to improve the mechanized mining degree of thin seam and increase the output of thin seam [2].

In recent years, deep-hole blasting technology has been applied in underground coalmines, such as improving gas extraction by increasing permeability of high gas and low permeability coal seam [3-4], preventing coal and gas outburst [5-6], rock cross-cut coal uncovering under complex geological conditions [7], rock roadway excavating [8], hard roof caving mining [9-10] and so on. However, the
studies on the application of deep-hole blasting technology to the treatment of hard dirt band in coal seam are less and insufficient.

In this paper, based on the similar simulated experimental system, the comparative tests of deep-hole blasting with ordinary charge and shaped charge were carried out, and the mechanical properties of dirt band in different charge structures were systematically investigated. The research results can provide theoretical and experimental support for the weakening of dirt band by deep-hole blasting in thin seam containing hard dirt band.

2. Blasting Test of Damage to Dirt Band

2.1. Damage Mechanism of Dirt Band in Shaped Charge Blasting

The explosives mainly destroy rocks by means of shock wave, stress wave and detonation gas. The energy of ordinary charge blasting propagates irregularly around the blasting hole, so the blasting stress wave destroys both coal and dirt band. In the past researches, a part of the energy of ordinary blasting is dissipated in the coal seam, while which used to break the dirt band is not enough. In addition, in the coal seam with poor roof and floor conditions, the stress wave propagating to the coal seam may also cause the damage of roof or floor, causing accidents. On the basis of ordinary charge, the charge structure is changed by setting energy cavity, so that the energy accumulation effect is used to make the shock wave compress the shaped charge liner at the beginning of the blasting to produce the accumulated energy jet, which accumulates the blasting energy in the direction of the damage to dirt band and forms the directional crack, thus improving the damage degree of the dirt band, as shown in Fig. 1.

2.2. Experimental Specimens and Their Mechanical Properties

Similar simulated experimental system for blasting damage to dirt band is composed of test box, hydraulic reaction system, dynamic strain gauge and data acquisition system, as shown in Fig. 2. In order to analyze the effect of blasting stress wave on the dirt band under two kinds of charge structures, two identical specimens were constructed, making charge structure was the only variable in the comparative experiment. The internal dimension of the test box is 120 cm (length) × 90 cm (width) × 90 cm (height).

In order to make the similar simulation test have better similarity with the actual engineering, the materials of the specimens need to satisfy certain similarity ratio with the actual material. According to the similarity criterion, the proportion relationships between similar materials and actual materials are

\[ \alpha_\sigma = \alpha_i \cdot \alpha_L, \quad \alpha_L = \frac{L_h}{L_m}, \quad \alpha_r = \frac{\rho_h}{\rho_m}, \quad \alpha_c = \frac{E_h}{E_m} = 1, \quad \alpha_\mu = \frac{\mu_h}{\mu_m} = 1 \quad \text{and} \quad \alpha_\psi = \frac{\varphi_h}{\varphi_m} = 1. \]

Where the subscripts \( h \) and \( m \) represent actual material and similar simulated material respectively; \( \alpha_i \) is...
the length scale ratio; $\alpha_r$ is the density ratio; $\alpha_\sigma$ is the stress ratio; $\alpha_\varepsilon$ is the strain ratio; $\alpha_\mu$ is the ratio of Poisson's ratio; $\alpha_\phi$ is the friction angle ratio.

![Figure 2. Similar simulated experimental system](image)

The actual materials in the experiment were taken from a coal seam containing dirt band in Shandong Province. The mechanical parameters of actual materials are shown in Table 1.

Taking compressive strength as the dominant index, the similar proportioning tests were carried out, and the proportioning parameters of the specimens are shown in Table 2. The mechanical parameters of each part of the specimens are shown in Table 3.

### Table 1. Mechanical parameters of actual materials

| Rock Properties | Density (g/cm$^3$) | Poisson's Ratio | Elasticity Modulus (GPa) | Compressive Strength (MPa) |
|-----------------|-------------------|-----------------|--------------------------|---------------------------|
| Sandstone       | 2.54              | 0.22            | 25.4                     | 62.5                      |
| Coal            | 1.38              | 0.29            | 4.5                      | 10.9                      |
| Dirt band       | 2.73              | 0.23            | 27.6                     | 98.8                      |

### Table 2. Ratio parameters of each material of similar simulated specimens

| Rock Properties | Sand | Cement | Gypsum | Water | Coal Powder |
|-----------------|------|--------|--------|-------|-------------|
| Sandstone       | 6.3  | 1.1    | 0.7    | 0.8   | 0           |
| Coal            | 3.7  | 0.5    | 1.0    | 0.7   | 1.3         |
| Dirt Band       | 3.6  | 1.7    | 0.4    | 0.7   | 0           |

### Table 3. Mechanical parameters of similar simulated materials

| Rock Properties | Density (g/cm$^3$) | Poisson's Ratio | Elasticity Modulus (GPa) | Compressive Strength (MPa) |
|-----------------|-------------------|-----------------|--------------------------|---------------------------|
| Sandstone       | 1.72              | 0.22            | 25.2                     | 2.82                      |
| Coal            | 1.61              | 0.29            | 4.6                      | 0.85                      |
| Dirt band       | 1.89              | 0.23            | 27.7                     | 4.56                      |

It could be obtained that $\alpha_r = l_s / l_w \approx 15$ after similar proportioning tests, from which the space size of the actual site that could be simulated by the specimen was $18 \text{ m} \times 13.5 \text{ m} \times 13.5 \text{ m}$. 

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2.3. Design of the Experiments

In similar simulated specimens, the thickness of roof and floor was 38 cm respectively; the coal seam was divided into upper and lower parts by the dirt band layer, each of which is 5 cm thick, and the thickness of the dirt band is 4 cm. The blasting hole was arranged in the dirt band. The diameter of the blasting hole was 16 mm, the depth was 450 mm, and the charge length is 200 mm. The hole was sealed with yellow mud and the sealing length of the hole is 250 mm. The shell of the explosive cartridge is a PVC pipe, which is filled with three-grade water-gel explosive and detonated by detonator. For the shaped charge blasting test, axisymmetric axial charge method was adopted for the cartridge, and two shaped charge liners which made of aluminum with thickness of 0.15mm were symmetrically arranged on the inner wall of the shell, as shown in Fig. 3. In addition, it should be ensured that the amount of explosive used in the comparative tests were the same.

Figure 3. Shaped charge explosive cartridge: (a) schematic diagram and (b) actual picture of shaped charge explosive cartridge (explosives not loaded).

The data acquisition system consisted of CS-1D super dynamic resistance strain gauge, TST3406 dynamic test analyzer and strain gauges. The strain gauges were arranged in the dirt band at 5 cm and 10 cm from the blasting hole horizontally and in the coal seam at 5 cm from the blasting hole vertically. The positions and numbers of the strain gauges are shown in Fig. 4. The specimens needed to be maintained for more than a month after finish manufacturing. Before the test began, the stress on the top of the specimen applied by hydraulic reaction system was to simulate the geostress of the actual site.
Figure 4. Schematic diagram of stress measurement points arrangement: (a) ordinary blasting and (b) cumulative blasting (unit: millimeter).

3. Analysis of Test Results

3.1. Analysis of Blasting Stress Evolution

Through the data acquisition system, the electrical signal curves of strain gauges in two tests were obtained. According to the inversion calculation, the electrical signal curves were transformed into the effective stress curves of each measuring point, as shown in Fig. 5.
Figure 5. Stress curves under different blasting charge structures: (a) #1 measuring point, (b) #2 measuring point, (c) #3 measuring point, (d) #4 measuring point, (e) #5 measuring point and (f) #6 measuring point

In Fig. 5, the negative value of the ordinate represents compressive stress and the positive value represents tensile stress. From the stress curve, it can be seen that the amplitude of the stress curve is larger at the initial stage of blasting, then as the time goes on, the direction of the stress wave changes, and the phenomenon of alternation of compressive stress and tensile stress occurs. After that, the amplitude decreases and finally tends to be stable. By comparing the stress curves of the corresponding measuring points in the two specimens in Fig. 5, it can be seen that the stress evolution of each measuring point of shaped charge blasting has changed greatly compared with that of ordinary blasting due to the different charge structures. In the direction of non-energy accumulation, the stress peak value \( P_4 \) of #4 measuring point is 6.82 MPa, while that of #1 measuring point \( P_1 \) is 8.74 MPa, and that is to say, the stress peak value decreases by 22%. In the direction of energy accumulation, the stress peak values of #5 \( P_5 \) and #6 \( P_6 \) measuring points are larger than those of #2 \( P_2 \) and #3 \( P_3 \) measuring points, which are 1.32 and 1.34 times higher than those of corresponding measuring points in ordinary blasting, respectively. The attenuation of peak stress of blasting stress wave with propagation distance should satisfy [12]:

\[
P = P_0 r^{-\alpha}
\]

(1)

Where \( r = r / r_e \), \( r \) is the distance of a point in rock from the center of the blasting hole; \( r_e \) is the radii of the blasting hole; \( \alpha \) is the stress wave attenuation index, \( \alpha = 2 - \mu / (1 - \mu) \) and \( \mu \) is the Poisson's ratio; \( P_0 \) is the impact stress on the inner wall of blasting hole when decoupled charge blasting.

The Eq. (1) is substituted from the experimental results \( P_2 = 10.46 \) MPa, \( P_3 = 3.32 \) MPa, \( P_5 = 13.8 \) MPa, \( P_6 = 4.46 \) MPa, and the error is small. In addition, in the vertical direction, when the stress wave enters the coal body from the dirt band, it needs to satisfy:

\[
P_r = P_v \left( \frac{\rho_2 C_2 - \rho_1 C_1}{\rho_1 C_1 + \rho_2 C_2} \right) \quad P_i = P_i \left( \frac{2 \rho_2 C_2}{\rho_1 C_1 + \rho_2 C_2} \right)
\]

(2)
Where $P_i$, $P_r$ and $P_t$ are the incident, reflected and transmitted waves, respectively; $\rho_1$ and $\rho_2$ are the densities of dirt band and coal, respectively; $C_1$ and $C_2$ are the velocities of P-wave of dirt band and coal, respectively.

When the stress wave reaches the interface between coal and dirt band, it will reflect and transmit. Because the wave impedance of dirt band is larger than that of coal, that is $\rho_2 C_2 < \rho_1 C_1$, from Eq. (2), it can be obtained that direction of reflected wave is opposite to that of incident wave. When the stress wave passes through the interface, a part of the stress wave is reflected to form tensile stress wave, which load reverse stress on dirt band. Therefore, the stress state of the dirt band near the interface is complex, and the damage to dirt band between blasting hole and interface is more serious under the mixed action of reflected tension stress wave and compression stress wave. As a result of the distances between #1 and #2 measuring points to the blasting hole are the same, and comparing the stress peak values, it can be seen that the stress peak value of #1 point after transmission is less than #2 point, which can make the stress wave transmission coefficient $T = \frac{2 \rho_2 C_2}{\rho_1 C_1 + \rho_2 C_2}$, so that $T = \frac{P_i}{P_t} = 0.84$.

3.2. Analysis of Crack Evolution

As shown in Fig. 6(a), after ordinary charge blasting, cracks spread irregularly along all directions around the blasting hole due to the radial outward propagation of blasting energy, so that there are irregular cracks in coal seam and dirt band, however, the cracks in dirt band are short and the scope is small. The measurement shows that the average length of cracks in coal body is about 35 mm, and that in dirt band is about 32 mm.

![Figure 6](image1.png)  
(a) Ordinary blasting  
(b) Shaped charge blasting

**Figure 6.** Crack development of specimens: (a) Ordinary blasting and (b) shaped charge blasting.
As shown in Fig. 6(b), after shaped charge blasting, more energy will be gathered in the dirt band in the direction of energy accumulation. Under the action of shock wave, the initial cracks appear in the rock around the blasting hole and the energy accumulation effect due to vertical compression of shaped charge liner by shock wave, so that the high-temperature and high-pressure accumulated energy jet begin to penetrate the initial cracks, forming the directional crack, after that, the directional crack creates a sudden vacuum, causing an inrush of a larger amount of detonation gas. Under the action of detonation gas and stress wave, the directional crack further expands outward, resulting in an obvious transverse long and wide main crack in dirt band. In addition, because most of the energy of blasting is gathered in the direction of energy accumulation, according to the law of conservation of energy, in the direction of non-energy accumulation, the energy of generating crack decreases, and only small irregular cracks can be formed in the coal body. The measurement shows that the average length of cracks in coal body is about 21 mm, and that in dirt band is about 57 mm. Compared with ordinary charge blasting, the length of crack in the dirt band of shaped charge blasting increases by about 1.8 times.

4. Conclusions
The main conclusions of this paper are as follows:

1) The similar simulation comparative tests of ordinary charge blasting and shaped charge blasting for the damage to dirt band in thin coal seam were carried out, and the results showed that the peak stress in the direction of energy accumulation of shaped charge blasting was 1.32 times that of ordinary blasting, while that in the direction of non-energy accumulation was 0.78 times of ordinary blasting.

2) In the case of the same charge quantity, the shaped charge blasting accumulated more blasting energy on the dirt band, so that the crack range in the dirt band was larger, and a long and wide main directional crack could be formed. The length of crack in the dirt band of shaped charge blasting was about 1.8 times that of ordinary charge blasting.

3) After shaped charge blasting in the dirt band, the stress waves reflected and transmitted on the interface between dirt band and coal, and the transmission coefficient is about 0.84, which reduced the energy of stress waves entering coal body. In addition, the characteristics of stress reduction in the direction of non-energy accumulation made the shaped charge blasting not only protect the roof and floor better, but also make the damage effect greater than that of ordinary charge blasting.

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