Experimental Research on Directional Blasting in Pre-cutting Hard Coal Seam Roof

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Abstract. Aiming at the problem of impact ground pressure caused by the hard roof of goaf in coal mining face, the research on pre-cutting of hard coal seam roof by directional blasting was carried out. According to the principle of energy accumulation in directional blasting, a similar simulated experiment was designed on the basis of theoretical analysis of stress wave propagation law, crack development law and forced roof caving distance. The experimental results show that the roof is pre-cut by directional blasting, the integrity of the roof in front of the working face is reduced, effective pressure relief effect is obtained, the large area of overhanging roof in goaf is prevented, and the impact ground pressure disaster of the working face is relieved.

1. Introduction
The accidents caused by the hard roof of coal seam in working face pose a great threat to the safety of coal mine production. Because of the high hardness, good integrity and fewer fractures of the roof, it is difficult to collapse. The large area of overhanging roof in goaf makes the coal wall and hydraulic support bear greater stress. Once the roof collapses, it will cause strong impact ground pressure and threaten the safety of workers and mining equipments, resulting in low mining efficiency, economic losses and waste of resources [1]. Therefore, in order to reduce the impact ground pressure caused by hard roof, it is necessary to change the law of roof collapse through manual intervention measures.

In order to solve the problem, scholars at home and abroad have carried out some researches in recent years. At present, the main methods adopted are water injection weakening [2], hydraulic fracturing [3-4] and blasting [5-7], etc. However, the papers on directional blasting applied to pre-cutting of roof are rare. In this paper, based on the energy accumulation principle of directional blasting, the directional blasting in pre-cutting hard roof by using the method of similar simulated experiment was studied. By directional blasting, the plane of weakness of roof was formed, so as to decrease the strength of roof rock and relieve the impact ground pressure, thus providing a technical method for pre-cutting hard roof in advance.
2. Theory of Directional Blasting In Pre-Cutting Hard Roof

2.1. Theory of directional blasting

When blasting in rock, shock wave, stress wave and detonation gas will be produced. Under the combined action of these factors, the rock around the blasting hole will be fractured and cracks generated, and vibration and rock joint development will occur in the farther area. Directional blasting is a kind of blasting with special charge structure. The blasting energy can be accumulated in a specified direction by setting a shaped charge liner, so as to increase the blasting damage effect in this direction, as shown in Fig. 1. After initiation, the shock wave will compress the shaped charge liner approximately vertically to form a high temperature and high pressure jet, which will create initial cracks in the surrounding rocks. After that, under the action of stress wave and detonation gas, a crack network with obvious directional crack as the main part and many branch cracks as the auxiliary part will be formed [8-9]. The Directional blasting results in a structural weakness in hard roof, forming stress concentration, further development of cracks and roof fracture, so that the falling area of roof is controlled and the impact ground pressure greatly is reduced.

![Figure 1. Schematic diagram of directional blasting in pre-cutting hard roof.](image)

2.2. Forced Roof Caving Step Distance in Directional Blasting

Pre-cutting hard roof refers to directional blasting in front of the working face, which destroys the integrity of the roof in front of the working face in advance. The forced roof caving step distance can be set within a reasonable and safe range by establishing a mechanical model [10]. Generally speaking, the roof rock and the coal can be simplified as a bearing beam model with coal wall as the fixed support and goaf as the simple support. The ultimate collapse distance of roof is as follow:

\[ L = H \frac{4R_t}{3q} \]  

Where \( H \) is the thickness of roof strata; \( R_t \) is the tensile strength of roof rock; \( q \) is the geostress load on roof. Considering the supporting capacity of hydraulic support, the efficiency of forced roof caving and the safety of the project, the step distance of forced roof caving is as follow:

\[ L_s = (0.5 \sim 0.6) L \]  

3. Experiment of Hard Roof Pre-cutting

3.1. Experimental Preparation

Similar simulated experimental system for pre-cutting of hard roof in directional blasting was composed of experimental box, hydraulic reaction device, dynamic strain gauge and stress gauge. The size of the
box was 1.2 m × 0.9 m × 0.9 m. It is necessary to correspond the physical properties of every part of the specimen with those of the actual materials when making specimen. According to Froude’s similar theory, the corresponding proportional relationship between similar materials and actual materials needs to be satisfied is \( \alpha_\sigma = \alpha_i \cdot \alpha_\gamma \). Where \( \alpha_\sigma \) is the stress ratio; \( \alpha_i = l_h / l_m \) and \( \alpha_\gamma = \gamma_h / \gamma_m \); \( \alpha_i \) is the length scale ratio; \( \alpha_\gamma \) is the density ratio. Subscripts \( h \) and \( m \) represent actual material and similar simulated material respectively. In addition, the proportion relationship that needs to be satisfied are \( \alpha_\varepsilon = \varepsilon_h / \varepsilon_m = 1 \), \( \alpha_\mu = \mu_h / \mu_m = 1 \), \( \alpha_t = t_h / t_m = \sqrt{\alpha_i} \). Where \( \alpha_\varepsilon \) is the strain ratio; \( \alpha_\mu \) is the ratio of Poisson's ratio; \( \alpha_t \) is the time ratio.

The actual materials were taken from a hard roof working face in Shanxi mining area. The mechanical parameters of coal, roof, floor and coal are shown in Table 1. According to the mechanical parameters of actual materials and the principle of similar proportioning, the ratio parameters of each material in the specimen were obtained by testing, as shown in Table 2, thus the mechanical parameters of each material of the specimen were obtained, as shown in Table 3.

### Table 1. Mechanical parameters of original materials

| Rock Properties | Thickness (m) | Density (g/cm³) | Poisson's Ratio | Elasticity Modulus (GPa) | Compressive Strength (MPa) |
|-----------------|---------------|----------------|----------------|-------------------------|---------------------------|
| Limestone (roof) | 8.0           | 2.58           | 0.27           | 31.2                    | 80.6                      |
| Coal            | 2.5           | 1.33           | 0.31           | 3.8                     | 11.5                      |
| Mudstone (floor)| 6.8           | 2.46           | 0.24           | 28.4                    | 38.7                      |

### Table 2. Ratio parameters of each material of specimen

| Rock Properties | Sand | Cement | Gypsum | Water | Coal Powder |
|-----------------|------|--------|--------|-------|-------------|
| Roof            | 6.3  | 1.2    | 0.7    | 0.8   | 0           |
| Coal            | 3.7  | 0.4    | 1.1    | 0.7   | 1.3         |
| Floor           | 7    | 0.6    | 0.6    | 0.7   | 0           |

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

| Rock Properties | Density (g/cm³) | Poisson's Ratio | Elasticity Modulus (GPa) | Compressive Strength (MPa) |
|-----------------|-----------------|----------------|-------------------------|---------------------------|
| Roof            | 1.84            | 0.27           | 31.2                    | 2.30                      |
| Coal            | 1.60            | 0.31           | 3.8                     | 0.55                      |
| Floor           | 1.77            | 0.24           | 28.4                    | 1.11                      |

It could be obtained that \( \alpha_i = l_h / l_m \approx 25 \) after similar proportioning tests, from which the space size of the actual site that could be simulated by the specimen was 30 m × 22.5 m × 22.5 m.

3.2. Design of the Experiment

In the process of laying similar materials layer by layer, the following points need to be noted. Firstly, two hollow cubic modules manually made of PVC expansion sheet were placed in the coal seam, after the specimen was preliminarily formed, the outer module was moved out, and the inner module was left in the coal to simulate the hydraulic support, while the roof of the goaf behind the support is suspended. Secondly, the blasting hole was located in the coal where near the interface between coal and roof. According to Equation (1) and (2), the forced roof caving step distance of the actual site was about 20 m, and it could be obtained by the length scale ratio that the distance in the specimen was 0.8 m. Thirdly, strain gauges were laid at the horizontal and upper positions 10 cm away from the blasting hole to monitor the effect of stress wave on the surrounding rocks in both horizontal and vertical directions after directional blasting. Finally, a stress gauge was embedded at the bottom of the coal under the blasting
hole, which monitored the stress load on the coal during a period of time before and after the blasting [11]. The schematic diagram of the similar simulated specimen is shown in Fig. 2.

![Schematic diagram of similar simulated specimen.](image)

Figure 2. Schematic diagram of similar simulated specimen.

The diameter of the blasting hole was 20 mm, the depth was 450 mm, the charge length was 200 mm and the way of radial uncoupling and axial coupling was adopted. The explosive cartridge was made manually, and the shell was made of PVC pipe and a shaped charge liner which made of aluminum with the thickness of 0.15 mm was pasted on the inner wall of the shell, as shown in Fig. 3. In order to improve the penetration depth of blasting, according to previous literatures, the angle of the shaped charge liner should be smaller, and the experiment was set at 50 degrees. The explosive cartridge was filled with water-gel explosive and detonated by detonator.

![Explosive cartridge: (a) schematic diagram and (b) picture of similar simulated explosive cartridge (explosives not loaded).](image)

Figure 3. Explosive cartridge: (a) schematic diagram and (b) picture of similar simulated explosive cartridge (explosives not loaded).

4. Analysis of Experimental Results

After the specimen has been maintained to the optimum state, the hydraulic reaction device is started to simulate the stress field, connect the data monitoring equipments, fill the explosive cartridge, and the experiment begins.

4.1. Analysis of Blasting Stress Evolution

Through dynamic strain gauge and data analyzer, the strain changes in the radial direction of the blasting hole of each measuring point after blasting were obtained. By inversion calculation, the stress curves were obtained, as shown in Fig. 4.
As can be seen from Fig. 4, under the action of blasting shock wave, the surrounding rocks are firstly subjected to compressive stress. Because the distance between the two measuring points and the blasting hole is the same, the time taken to reach the peak stress is basically the same. As time goes on, the magnitude and propagation direction of the stress wave change constantly, and the phenomenon that the compressive stress and tensile stress change alternately and the stress amplitude decreases gradually appear.

The measuring point in coal is in the direction of non-energy accumulation, and its peak stress is 10.34 MPa, while the measuring point in roof is in the direction of energy accumulation, and its peak stress is 5.04 MPa. It can be seen that in directional blasting, the blasting energy is greatly accumulated in the direction of setting the shaped charge liner, and under the penetration of the energy jet, a greater peak stress is produced. In addition, as the blasting hole is located in the coal, the stress wave needs to pass through the interface between coal and roof rock. Because the wave impedances of coal and roof rock are difference, the stress wave will be reflected and transmitted, and then there are:

\[ R = \frac{\rho_2 C_2 - \rho_1 C_1}{\rho_1 C_1 + \rho_2 C_2} \]

\[ T = \frac{2 \rho_2 C_2}{\rho_1 C_1 + \rho_2 C_2} \]

\[ 1 + R = T \]

Where \( R \) and \( T \) are the coefficient of reflection and transmission, respectively; \( \rho_1 \) and \( \rho_2 \) are the densities of coal and roof rock, respectively; \( C_1 \) and \( C_2 \) are the velocities of P-wave of coal and roof rock, respectively. Because \( \rho_1 C_1 < \rho_2 C_2 \), from Equation (3), the reflection coefficient is positive and \( T > 1 \), that is, the direction of reflected wave is the same as that of incident wave, and the compression wave will still be compression wave after passing through the interface, thus the stress is enhanced by superposition. Without considering the attenuation difference of stress wave in the direction of two measuring points, the enhancement coefficient of the peak stress in the direction of energy accumulation relative to that in the direction of non-energy accumulation is as follow:

\[ P_2 = kTP_1 \]

It can be obtained that \( T = 1.10 \) by substituting wave impedance of coal and roof rock into Equation (3), so that the enhancement coefficient is 1.86 from Equation (4).

4.2. Analysis of Stress Variation

The stress changes of coal and rock mass before and after blasting are recorded by stress gauge, so as to judge the effect of blasting on confining stress field of coal. In Fig. 2, point P is the measuring point of stress gauge. According to the similar ratio of time, namely \( \alpha_i = \sqrt{\alpha_i} = 5 \), the stress value can be
recorded every two minutes to simulate the stress value of the site every ten minutes, and the measured values one hour before and after blasting are counted. From Fig. 5, it can be seen that the stress is obviously relieved after blasting. The average stress before and after blasting is about 1.44 MPa and 1.06 MPa, respectively. It shows that directional blasting has destroyed the roof structure and changed the original stress field, thus reducing the confining stress in coal by about 26%.

4.3. Analysis of Crack Development

Previous studies have shown that different angles of shaped charge liner have great influence on blasting effect. Based on the characteristics of directional blasting in cutting roof, the aim of improving the mass and speed of energy jet and increasing the length of penetrating cracks is achieved by setting a smaller angle. In the direction of energy accumulation, due to the penetration of energy jet, a larger initial crack is formed. Then, under the action of stress wave and gas wedge of high temperature and high pressure detonation gas, the cracks extend along the direction of the initial crack, thus forming the tip stress concentration, which promotes the further development of the cracks, as shown in Fig. 6.

Through experimental observation, directional blasting produces vertical main fissures in roof rock, which are accompanied by many fissure branches. The total length of the fissures is about 23 cm. However, no obvious cracks are found in surrounding rocks around the blasting hole in other directions.
5. Conclusion

The main conclusions of this paper are as follows:

1) In this paper, through similar simulated experiment, aiming at the problem of large area of overhanging hard roof causing impact ground pressure, the pre-cutting of roof in advance by directional blasting was carried out. It is found that the peak stress of directional blasting in the direction of energy accumulation is 1.86 times than that of non-energy accumulation direction. In the process of stress wave passing through the interface between coal and roof rock, the peak stress is enhanced, which greatly increases the blasting energy in the direction of energy accumulation.

2) The maximum step of roof collapse was calculated theoretically by building the bearing beam model, and the forced roof caving step distance was set accordingly. According to the stress changes in coal before and after blasting, it can be seen that the cutting of the roof by directional blasting can relieve the pressure of the coal, and the reduction of stress can reach 26%.

3) After blasting, a main crack accompanied by many branch cracks was produced in the roof rock, while other areas were relatively intact. Although the cracks do not completely penetrate the whole roof, they fully change the integrity of the roof and provide a plane of weakness for the future roof collapse. Therefore, the directional blasting in pre-cutting hard roof can weaken the roof in advance without affecting the mechanized working face, and prevent the impact ground pressure disaster.

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