Research Article

Research and Application of Integrated Presplitting Blasting in Nonpillar Mining Technology

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This article introduces a technology of integrated presplitting blasting, which can be applied to a new nonpillar coal mining method (i.e., Gob-side Entry Retaining by Roof Cutting (GERRC)) under the condition of thick and hard roofs. First, the new nonpillar coal mining method emerging in China is explained. Then, the concept of integrated presplitting blasting was put forward, and the mechanism of the technology was explained by the method of numerical simulation. Through a mining case with a thick hard limestone roof, the relevant design of nonpillar mining and the design parameters of integrated presplitting blasting are explained in detail. After field practice verification, from the construction process and test results, as well as combined with underground pressure observation and analysis, it shows that technology and design are reasonable. This research supplements the mining technology system of coal mining engineering and the proposed technologies and methods have strong applicability, especially for related coal mines nonpillar mining and safe and efficient mining.

1. Introduction

Gob-side Entry Retaining by Roof Cutting (GERRC), a new nonpillar coal mining method, is considered a very promising mining technology [1–9], which have been applied to a large number of coal mines. Compared with general coal mining methods, nonpillar mining has obvious technical advantages. For example, using this method can realize the economic benefits of digging one less roadway for each working face and recovering one more coal pillar. At the same time, this technology greatly reduces the roof disaster problem and reduces hazards such as ventilation and gas accumulation. This technology has significant safety benefits and social impact and is considered to be the third mining science innovation [9].

There are basic researches [8, 10–14], laboratories [15–17], and field engineering [18–23] around this new type of coal mining [24, 25]. At present, this new nonpillar mining technology has been successfully applied to various geological conditions and different roof conditions. However, there are few in-depth studies on nonpillar coal mining with thick and hard roofs.

Thick and hard roofs are widely distributed in coal mines, which account for 1/3 of the proportion of coal mines in China. These rock layers are generally thick-layered as a whole, and the bedding, joints, and cracks in the rock mass are not developed. A common disaster for thick and hard roofs is that they fail to collapse in time, resulting in large-area overhangs of the roof, posing safety hazards to coal mines. Thick and hard roof mining generally requires special technology to weaken the roof [26–28].

The thick hard direct roof is a kind of catastrophic roof, and there are many challenges in Gob-side Entry Retaining by Roof Cutting (GERRC) coal mining under this roof condition [18]. First of all, the integrity of thick hard direct roof is strong and the lithology of the roof is extremely hard. Such a roof is not easy to break and collapse, which is difficult to form roadway. Secondly, the intensity of ground pressure in the mining of thick hard roof is very severe. The
thick hard roof has strong self-stabilizing ability and is not easy to slump, which leads to the increase of the overhanging area of the goaf and the multiplication of the pressure. Such roof pressure has a huge impact on the roadway impact. Finally, the gobbs with thick and hard roofs have huge rock blocks falling at one time. The height of rock blocks can reach 3 m, and the maximum length and span can reach 25 m, which seriously impact and damage the gangue retaining structure in the roadway. Therefore, the study of thick and hard roof control technology is of great significance for the promotion of nonpillar coal mining.

2. New Nonpillar Coal Mining Method (110-Method)

In general longwall coal mining methods, two roadways need to be excavated in advance for a working face [29]. During the mining process, the two roadways collapsed as the rocks in the mined-out area collapsed. To avoid the impact of the supporting pressure of the coal pillars on the overlying rock on the coal mining activities of the new work, it is necessary to leave a sufficient distance of coal pillars, to replan the working face, and excavate two roadways at the next working face. This kind of coal mining method also is known as the 121-method, as illustrated in Figure 1.

The new nonpillar coal mining method makes full use of rock mechanics. Through certain technical measures (Gob-side Entry Retaining by Roof Cutting (GERRC)), the roadway of the working face is fully relieved and effectively supported during the mining process, and the roadway of this working face is reserved and can be used continuously on the next working face.

This new mining method is known as 110-method [9], and it avoids wasted coal pillars, saves an excavation roadway, and optimizes mining time. It is an advanced mining method that greatly promotes coal enterprises to reduce costs and increase benefits.

3. Integrated Presplit Blasting Technology

3.1. Technical Background. In the process of nonpillar coal mining, the reserved roadway needs to be fully and effectively relieved of pressure, which requires the roof of the mining area to collapse in time, thereby reducing the pressure on the roadway. In this case, the collapsed gangue can timely provide support for the roof above the roadway.

The thick and hard roof structure will cause the roof cantilever to be larger, and the roof often fails to collapse in time after mining, which causes greater safety hazards to the roadway. As shown in Figure 2(a), if the suspended roof is not treated, it will cause pressure on the roadway and cause excessive deformation of the roadway. At the same time, if a large area of the roof collapses, huge rocks will be formed. The big rock impacts the side support of the roadway, which has a great impact on the quality of the roadway formed by nonpillar mining.

For roadway in nonpillar mining with a hard roof, to avoid the large suspended roof area and the impact of large broken rocks on the roadway, integrated presplitting blasting technology is designed. As shown in Figure 2(b), the integrated blasting technology first needs to cut off the roof using ① roof-cutting blasting. This step is also a key technology in all general nonpillar mining. For the integrated presplitting blasting technology of the hard roof, it is necessary to increase the design ② shallow hole blasting before the working face support to fragmented regional roof. The purpose of this step is to create cracks in the roof and weaken the strength of the roof and reduce the span of the roof and the pressure when it collapses. At the same time, the blasting cracks the roof near the roadway, which can reduce the rock mass on the side of the roadway. This can accelerate the collapse of the roof and quickly realize roadway retention.

Figure 3(a) shows a plan view of the integrated presplitting blasting technology, and Figure 3(b) shows a three-dimensional view of the design. Figures 2 and 3 vividly show the two key steps of this technology, and the technical principle and implementation method are simple.

3.2. Principles of Integrated Presplitting Blasting Technology. Integrated presplitting blasting technology is divided into two parts. The first is to use directional presplitting technology to cut the roof above the goaf and roadway, and the second is to blast the roof above the working face in the goaf. The purpose of the two to the rock after blasting is different, and the mechanism of blasting the rock is also different.

Figure 4(a) shows the principle of rock fragmentation by blasting. The purpose is to create a large number of cracks in the roof in the blasting area, and it is required to fully weaken the strength of the roof. This technology uses explosives to form blasting damage to the rock and form cracks in the roof, weakening the integrity and strength of the roof.

Figure 4(b) shows the principle of directional energy-accumulation presplitting blasting rock. The purpose is to cut off the roof of the roadway and the roof of the goaf in a directional direction, which requires the effect of directional cracking. The core of this technology is the use of special PVC pipes (energy gathering pipe), which can accumulate blasting energy through energy-collecting holes and enhance the jet direction of blasting. By continuously blasting a plurality of energy-concentrating presplit holes, the cracks between the holes can be penetrated to form a directional cutting surface, and the result of cutting the roof can be realized.

3.3. Numerical Simulation of Integrated Presplitting Blasting Technology. The difference between directional blasting and fragmentation blasting is that the energy gathering pipe affects the shock wave and blasting gas at the initial stage of blasting, thereby affecting the initial fracture damage that acts on the rock mass. The energy gathering pipe has a directional energy-gathering effect, which strengthens the initial crack in the energy-gathering direction and protects the hole wall from the explosion in the non-energy-gathering direction; thereby only directional crack is produced.

The method of numerical simulation can intuitively study the mechanism of the two initial stages of blasting [30–32]. The general finite element software Abaqus is used to simulate the blasting process, and the Euler algorithm is
used to divide the space into fixed grids through which materials can pass.

Air is an ideal gas model. The equation of state of the ideal gas is defined as follows [33]:

\[ P = (\gamma - 1) \frac{P_0}{\rho_0} E. \]  \hspace{1cm} (1)

In the formula, \( P \) is the pressure; \( \gamma \) is the adiabatic index, \( \gamma = 1.4 \); \( E \) is the gas internal energy; the air density is 1.225; the reference temperature is 288.2 K; the specific heat capacity is 717.5999976 J/(kg \cdot K).

The simulation of explosives is expressed by the JWL equation of state [33]:
Figure 3: (a) Plan view of the integrated presplitting blasting technology design. The shallow hole blasting before the working face support is to fragmented regional roof, and the roof-cutting blasting on the side of the road is to cut off the roof of the roadway and goaf. (b) Three-dimensional view of the integrated presplitting blasting technology design, which allows for a more intuitive display of design ideas.

Figure 4: Principle of integrated presplitting technology. (a) Fragmentation blasting. The shallow hole blasting is to fragmented regional roof, which is to create cracks in the roof and weaken the strength of the roof, and reduce the span of the roof and the pressure when it collapses. (b) Directional cutting roof blasting. This roof-cutting blasting uses special PVC pipes (energy gathering pipe) to form a directional cutting surface, and the result of cutting the roof can be realized.
\[ P = A \left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E_0}{V}. \] (2)

In the formula, \( P \) is the pressure; \( V \) is the relative volume; \( E_0 \) is the initial specific internal energy; and \( A, B, R_1, R_2, \omega \) are the material constants.

The simulation of the energy gathering pipe adopts the Rankine–Hugoniot damage model [34] of the polymer material impact state equation, and the Gruneisen coefficient is 0.87. The energy gathering pipe adopts the von Mises yield criterion, the yield stress is \( 5 \times 10^4 \) kPa, and the pipe suffers from large deformation failure.

The concrete damage model (Johnon–Holmquist damage model) is used to simulate the rock. The constitutive relationship can be described as [35]

\[ \sigma^* = A (1 - D) + B \left(\frac{p^*}{f_c}\right) \left(1 - c \ln \varepsilon^*\right). \] (3)

In the formula, \( \sigma^* = \sigma / f_c \) is the ratio of actual equivalent stress to static yield strength; \( D \) is the damage parameter; \( p^* = p / f_c \) is dimensionless pressure; \( \varepsilon^* = \varepsilon / \varepsilon_0 \) is the dimensionless strain rate; \( A \) is the normal viscosity coefficient; \( B \) is the normal pressure hardening coefficient; and \( c \) is the strain rate coefficient.

The cumulative damage of the model is described by equivalent plastic strain and plastic volume strain as [35]

\[ D = \sum \frac{\Delta \varepsilon_p + \Delta \mu_p}{D_i (\varepsilon^* + \mu^*)^D_i}. \] (4)

First, simulate the effect of explosive blasting in the air. Figure 5(a) shows the blasting effect of the device without the energy gathering pipe, and Figure 5(b) shows the blasting effect of the energy gathering pipe device. It can be seen from 5(a)-B and 5(a)-C that the initial shock wave generated by the explosive blasting in the air without the addition of the pipe device blasts in an isotropic circle along the surroundings, and the explosive material also propagates in an isotropic circle around it. The energy spreads in all directions.

It can be seen from 5(b)-B and 5(b)-C that by adding the energy gathering pipe blasting device, the blasting shock wave propagates outwards at the location of the directional energy gathering opening, while the nondirectional energy gathering pipe prevents the shock wave from spreading outward. It can also be seen from the propagation speed of the explosive product that the energy is concentrated in the energy-gathering direction, and the speed of the explosive product only propagates in the energy-gathering direction and is blocked by the pipe wall in the non-energy-gathering direction. It can be seen that the energy-concentrating pipe directly affects the movement of the blasting object in the initial stage, so as to protect the hole wall from the impact of blasting in the nondirectional direction.

Then, under two blasting conditions, the explosion damage produced by blasting on the rock is simulated. As can be seen in Figure 6(a), the explosive blasting has caused initial damage and cracks around the hole wall. The stress of blasting is concentrated around the hole wall. The yield of the rock mass is also isotropic. The stress field generated by blasting isotropic propagation expands the internal cracks in the rock mass.

As can be seen in Figure 6(b), the addition of the energy gathering pipe protects the integrity of the hole wall in the non-energy-collecting direction. The force is only concentrated at the location of the energy-gathering opening, and the rock hole wall damage and cracks caused by blasting are only generated in the direction of energy-gathering. The stress field of blasting and the energy transmission to the rock mass will promote the tension of the cracks in the hole wall and finally form longer cracks.

4. Engineering Background and Design

4.1. Project Overview. The test working face is Shanxi Yixin Coal Mine, located in Shanxi Province, central China. As shown in Figure 7, it is a modern integrated mechanized mining coal mine with an annual output of 3 million tons. The test working face is 1306 working face, as shown in Figure 8(a). The length of the working face is 200 m, and the roadway reserved for nonpillar mining is 461 m. The mining roadway has a rectangular section of 5.2 m × 2.6 m and adopts the support method of “anchor cable-bolt-plastic net.” The support section is shown in Figure 8(b).

From the integrated lithology histogram of the working face (Figure 8(c)) and the natural gamma log, it can be seen that the roof is directly located on the coal seam, and the lithology K2 limestone has an average thickness of 8.9 m. The roof diagenesis is well consolidated, the texture is hard, and the roof has high shear and compressive strength. The falling rocks are large in size and strong in integrity. When forming the coal seam roof, it is a hard roof that is not easy to fall, and the roof is suspended during the mining process. The upper part of K2 limestone has a soft rock and coal seam interlayer close to 2.1 m, which is relatively soft. Further up there is a thick layer of K3 limestone with a hard texture.

4.2. Design Parameters of Nonpillar Mining. The lithology distribution of the roof is the most important basis for the design of key parameters of pillarless mining. The lithology within 15 m of the roof of 1306 working face was drilled and photographed, and the data and information obtained were drawn into the roof lithology geological section map as in Figure 9(a).

It can be seen from the figure that the K2 limestone on the roof of the roadway is about 9 m at the position of 0–50 m. The K2 limestone thickness of the roadway roof at the position of 100–200 m reaches 11–12 m thick. K2 limestone thickness of the roadway roof at the position 250–450 m is 8–10 m. There are obvious primary joints in K2 limestone at 3–5 m, and the separation cracks of the roof can be seen through photography in the hole, and the joints are filled and cemented by quartz minerals. For areas with large changes in roof lithology, roof coring is performed to supplement and verify the geological profile.

Two parameters are designed according to the roof lithology. The overall design adopts as shown in Figure 9(b).
Figure 5: Simulation of explosive blasting in the air: (a) without adding energy gathering pipe and (b) by adding energy gathering pipe.

Figure 6: Simulation of blasting damage to rock: (a) without adding energy gathering pipe and (b) by adding energy gathering pipe.
The constant resistance anchor cable is 12.3 m long. The blast hole length of the directional cutting roof is 10 m, the cutting height is above the hard limestone roof (the limestone thickness is 8.9 m), and the drilling angle is 75°. In local areas (such as 100–200 m position), the length of the constant resistance anchor cable is adjusted to 15.3 m, the height of the blast hole is adjusted to 12 m, the height of the blast hole is above the hard limestone roof (the thickness of limestone is 11.5 m), and the drilling angle is 75°. See the next section for the detailed construction process.
Figure 9: Roof lithology description and nonpillar mining design parameters. (a) The lithology within 15 m of the roof of 1306 working face was drilled and photographed to form the lithology geological section map, which is the most important basis for the design of key parameters. (b) Two parameters are designed according to the roof lithology. The constant resistance anchor cable is designed in three columns and 12.3 m long. The blast hole length of the directional cutting roof is 10 m and the drilling angle is 75°.
4.3. Integrated Presplit Blasting Parameters. Figure 10 shows the integrated presplitting blasting design under the hard roof. The integrated blasting includes the deep-hole directional presplitting blast hole that cuts off the roof and the shallow-hole blasting in front of the working face support used to break the roof.

The B-B section is a schematic diagram of the blast hole cut off the roof. The selected explosive parameters are $\Phi 32 \times 200$ mm, 200 g/roll, and the diameter of the blast hole is 50 mm. It needs to use 6 specially made energy-gathering pipes. The charging structure is 2-3-4-4-3-2. The charging parameters are shown in Table 1. The blast hole spacing is 500 mm, and 8 holes are detonated at a time. For details of the charge, refer to similar related documents, which will not be repeated here.

The A-A section is a schematic diagram of the shallow hole fragmentation blasting roof in front of the hydraulic support of the working face. The diameter of the blast hole is 35 mm, and the charging parameters are shown in Table 1. The shallow blast hole spacing is 750 mm, and 10 blast holes are detonated at a time. There is no need to add energy gathering pipe, only needs to continuously charge in the hole according to the designed amount.

5. Field Test Result

5.1. Nonpillar Mining Process. Figures 11(a)–11(e) show the entire process of thick and hard roof nonpillar mining. From Figure 11(d), it can be seen the complete process of the thick and hard limestone roof falling smoothly behind the support of the working face after precracking.

The overall construction sequence is as follows: applying constant resistance and large deformation anchor cable (CRLDA) → roof presplitting and slitting → roof shallow hole blasting → hydraulic supports in the roadway → after the working face is mined, the roof of the goaf gradually collapses → the roof of the goaf completely collapse → the roadway is stable, and the hydraulic supports are withdrawn.

The overall construction sequence does not affect each other, and the field application is good. It shows that under the condition of thick and hard limestone roof, the use of...
Figure 11: Continued.
integrated presplit blasting technology can achieve safe nonpillar mining.

5.2. Cutting Roof Presplitting Blasting Effect. The cut-roof effect of blasting requires the use of in-hole photography equipment. It is used to check the crack formation effect in the hole after blasting, to verify the blasting quality of the cut-off roof. Figure 12(a) shows the entire schematic diagram of the operation. The camera is used to collect the image in the hole, and the wheeled electronic pedometer is used to record the peeping depth. By peeking the results on the spot, the blasting personnel can adjust the blasting parameters at any time to achieve the best crack effect. Figure 12(b) is a photo of the entire instrument.

Figure 13(a) shows the actual operation of underground workers. The specific operation can be realized by only 1 to 2 personnel, and the operation is simple.

The effect of cutting off the roadway roof can be seen from the figure. Figure 13(b) shows the effect of the roof surface after the roof is precracked. After blasting, a through crack is formed on the roof surface, which cuts the roof of the roadway and the roof of the goaf. Figures 13(c) and 13(d) show the effect of presplitting and cracking in the hole. There are two clear and symmetrical cracks in the hole, which extend from the bottom of the hole to the top of the hole. Two cracks in the hole cut the hole, and the hole and the hole crack penetrated to achieve the effect of cutting off the roof.

5.3. Pressure Monitoring of Hydraulic Support. By monitoring the pressure of the working face hydraulic support, the effect of presplitting blasting is analyzed.

Figure 14(a) shows a schematic diagram of the installation and layout of the hydraulic support, and the positions of the 12# and 14# hydraulic supports for comparison.

Figure 14(b) shows the time-space pressure cloud graph curve of pressure with the mining distance of the working face. It can be seen that the periodic pressure is obvious, with a certain distance. Each cycle of the roof pressure represents the periodic break of the roof. When the pressure reaches its peak during the cycle, it indicates that the roof is broken. By
analyzing the ups and downs of curved surface, it can be known that the initial pressure distance is 36 m and the periodic pressure distance is 10~15 m.

Figure 14(c) compares the pressure of the 12# and 122# hydraulic supports. The two hydraulic supports are located at both ends of the entire working face, almost symmetrically distributed. Among them, integrated presplit blasting technology was carried out in the area of 12# hydraulic support, but not in the area of 122# hydraulic support. By comparing the pressure changes of the two hydraulic supports, the pressure relief effect of the integrated presplit blasting technology can be compared. The overall force of the 12# hydraulic support is
significantly less than the pressure of the 122# hydraulic support. The average pressure of the 12# hydraulic support is 17.3 MPa, and the average force of the 122# hydraulic support is 21.1 MPa. From the figure, it can be concluded that the integrated presplitting blasting has an obvious pressure relief effect.

5.4. Roadway Deformation Monitoring. Displacement measurement of the roadway can get the deformation of the roadway in the process of mining without coal pillars, which can be used to judge whether the roadway is stable and meet the use of the next working face. Figure 15(a) shows the cross-point method of measurement and the actual measurement situation of on-site workers.

Figure 15(b) shows the measurement curve of the roof and floor deformation of the roadway. It can be seen from the figure that, similarly, the roadway changes significantly before the mining advancement distance of 90 m in the working face, and the deformation is stable after the mining advancement is 130 m. The total deformation of the two sides of the roadway is 151 mm, of which the bulge of the coal wall is 135 mm, and the displacement of the side gangue of the goaf is 16 mm.

The roadway can remain stable after the working face is advanced for 200 m, and the overall deformation after stabilization is not large, which can satisfy the next working face to use this roadway. It shows that nonpillar mining under the condition of thick and hard limestone roof has been successfully realized.

6. Conclusions

Following conclusions were obtained through this research:

(1) The attribute of the thick and hard roof leads to a large suspended roof span and the roof is not easy to collapse. Integrated presplitting blasting technology
is designed. Through the combination of cutting roof directional blasting and shallow hole fragmentation blasting, the roadway roof can be retained and the goaf can accelerate the collapse of the roof.

(2) The mechanism of integrated presplitting blasting technology is explained from the design ideas and numerical simulation methods. The mechanical behaviors of the two steps of directional cutting roof presplitting blasting and shallow-hole fragmentation blasting were compared and analyzed, including the propagation state of explosives in the air, as well as the fragmentation of rocks and the formation of cracks. The stress field of blasting, energy expansion, and initial damage state of rock can be changed by adding energy gathering pipe, thus affecting the formation of cracks in blasting.

(3) The field test results are good, the roof cracks are obvious, the directional presplitting effectively cuts off the roof, and the integrated presplit blasting technology reduced the pressure of the hydraulic support on the working face. The results show that the roof of the goaf can collapse in time after adopting the new technology, which increases the safety of nonpillar coal mining.

Data Availability
No data were used to support this study.

Conflicts of Interest
The authors declare no conflicts of interest.

Authors’ Contributions
Manchao He, Guodong Mei, and Xuyang Xie conceived and designed the research. Sha Wang and Xiaoyu Liu performed field tests; Xiaoyu Liu analyzed the data and wrote the paper.

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