Study on a High-Efficiency Mining Technology System for Gas Outburst in Coal Seams—Example of an H Coal Mine

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Abstract: Coal will continue to play an important role in China’s economic development and social development in the coming decades. However, due to the complex distribution conditions of coal resources, the mining of coal resources is subject to various restrictions. Coal and gas outburst is an important issue in coal mining, and the threat to the mining of coal resources caused by high gas outburst activity has been receiving more attention. In order to solve the problems related to safe and efficient mining under coal seams with gas outburst, such as mining difficulties, large amounts of work, resource waste, no guaranteed gas treatment time, and low economic efficiency, it is necessary to innovate mining technology and methods for managing gas outburst in coal seams to improve the efficiency of coal mines and to solve the above problems. This study proposes a green mining technical method system known as the “L-H method”, which is applicable to the safe and efficient mining of coal seams with gas outburst based on combined theoretical analysis and numerical simulation. The following research results are achieved: (1) The “L-H method” is proposed, and a mining area model of coal seams with gas outburst is established. The specific details of the method and the implementation process are introduced. (2) Examples of H coal mine applications are presented, and the effects of the implementation of the “L-H method” are analyzed and summarized through mine pressure observations from roadways, and it is concluded that the implementation of top-cutting and pressure-relief technology has a good control effect on the roadway-surrounding rock and that gas extraction reaches the national standard of less than 8 m3/t for protrusion prevention; this ensures safety and also achieves efficient mining. This study will provide a good reference for the implementation of green mining methods to similar coal and gas outburst mines.

Keywords: gas outburst; coal seam; green mining; gob-side entry retaining; layer-by-layer gas extraction

1. Introduction

Gas protrusion mines account for about half of the coal mines in China. Gas is the biggest threat to coal mine safety, and more than 70% of major safety accidents in coal mines nationwide are related to gas explosions. According to the current gas seam mining technology, a rock-bottom extraction lane has to be dug in the bottom rock before mining the gas-accentuated coal seam, causing a large amount of roadway digging work and slow gas extraction speeds and affecting the success of the mining working face. Roadway digging has a negative effect on the economic benefits of coal mines, so research on how to mine gas-accentuated coal seams safely and efficiently is of particular importance.

In order to solve excavation and gas problems in gas-herniated coal seam mining, researchers have explored methods to manage gas-herniated coal seams on the basis of ensuring safety around the world [1]. Wang and Cheng et al. studied gas management in a high-gas-herniated coal seam group to determine the geological conditions of the
Xin zhuangzi coal mine in a Huainan coalfield and introduced a key technology for safe coal seam mining [2]. Li introduced a new method to reduce the risk of coal and gas protrusion and to improve gas extraction and utilization in coal mines, and the application results showed that thin self-protected seam mining can effectively eliminate the risk of coal and gas protrusion and improve gas extraction and utilization [3]. In order to mitigate gas disaster and eliminate the risk of gas protrusion, Wang and Lu et al. proposed a gas protrusion safety strategy. Additionally, they also established a three-dimensional gas extraction and utilization safety engineering system. The results showed that the proposed safety strategy could effectively reduce the risk of protrusion in strongly protruding coal seams and that it could extract and utilize a large amount of unloading gas [4]. Luan and Jiang et al. studied the roadway deformation mechanism in their studied mining area and proposed a method to improve the speed along the roadway, which solved serious deformation problems along the studied roadway [5]. Liu and Liu et al. developed a combination of ultra-thin protection coal seam drilling and unloading gas extraction to prevent and control coal and gas protrusion disasters [6]. Chang and Tian proposed a pressure relief gas extraction technical model of a typical mining area based on the simultaneous gas extraction theory to ensure that gas was discharged from the outburst coal seam quickly [7]. Neil and David et al. proposed a methodological framework for modeling the hydrological impacts of coal seam gas extraction on downstream river flows [8]. Yao and Ma et al. studied the gas transport rule under the effects of protective coal seam mining. This study has important engineering significance for coal seam gas migration protection laws and provides a reference for controlling coal and gas outburst in deep-mining activities in China [9]. Fan and Li et al. established a stress–seepage–damage coupling model that is able to simulate the evolution process of the dynamic coal and gas outburst system. This research is of great importance for the formulation of coal and gas outburst predictions and plays a guiding role in the development of prevention measures [10]. In summary, scholars mainly study how to control, predict, and prevent gas outburst in coal seams, and the innovation of mining technology for gas outburst in coal seams is lacking. Additionally, the researchers have conducted research specifically on gas management techniques or on along-air retention techniques, but in reality, some gas mines require both gas treatment and gob-side entry retaining methods of innovation, which require a system that can effectively combine the two technologies [11,12].

Gas problems are the first conflict that must be solved in mining coal resource in high-gas areas, and how to achieve safe and efficient mining is the main goal of this paper. Due to the special mining conditions in high-gas areas, coal mines consume large human, financial, and material resources as well as time costs to control gas, and the success of coal mining is harshly evaluated, which seriously affects the production efficiency of coal mines [13,14]. Therefore, in order to improve the production efficiency of coal mines and alleviate the problems related to coal mining success, it is necessary to innovate technologies and methods for mining coal seams with gas outburst to ensure that the technology is applicable, safe, reliable, economical, and reasonable, and to provide sufficient time and space for gas extraction in coal mines. In this paper, a technical method that is suitable for coal seam mining with gas outburst is innovated on the basis of gob-side roadway retention by combining theoretical analysis and numerical simulation, and its effect and feasibility are verified.

In summary, this study introduces a new method for the safe and efficient mining of gas-accentuated coal seams—the “L-H method”. The most important feature of this method is that it combines gas control and gob-side entry retaining technology.

2. Methods

According to the State Administration of Mine Safety, forty-four people have been killed in eight coal and gas outburst accidents in the provinces of Guizhou, Yunnan, Shanxi, Heilongjiang, and Henan in the past two years. Coal and gas outburst refers to the phenomenon in which there is a sudden outburst of coal and gas from inside the coal
wall to the mining face in a short period of time, causing immeasurable casualties and serious losses. The causes of coal and gas outburst are mainly the result of ground pressure, tectonic stress and mine pressure, gas content and gas pressure, and the physical and mechanical properties of rock and coal [15]. Many researchers have utilized new methods to study the mining methods targeting coal and gas outburst in coal seams. Yanqing Li et al. used the pressure-relief mining and gas extraction theories to solve the problem of “one hole and two eliminations” by drilling along the coal seam and “replacing roadway with hole” for drilling on the top of the mine. This innovative method for co-mining coal and gas reduced gas control costs by more than 30% [16]. Quangui Li et al. proposed a new pulse hydraulic fracturing technology with the aim of solving the coal and gas outburst problem to prevent gas hazards and promote gas extraction. Cross-measure boreholes are used to solve gas problems in the driving working face [17]. This paper puts forward that the “L-H method” is suitable for the safe and efficient mining of gas outburst in coal seams and describes the implementation process of the “L-H method” in detail. A mining model of coal seams with gas outburst is established, and the formula of the roadway driving amount and mining preparation time of the “L-H method” for coal seams with gas outburst is obtained. Compared to traditional mining methods, this method saves time and ensures safe and efficient mining.

2.1. Introduction to the Technical Content of the “L-H Method”

The two core technologies of the “L-H method” are gob-side entry retention and layer-by-layer drilling gas extraction. The objective to be achieved by the joint implementation of the two technologies is to leave only one rock-bottom extraction lane below the first mining face in the entire mining area. Figure 1a shows a schematic of the “L-H method” mining system.
Figure 1. Cont.
Figure 1. Process of “L-H method” (a) Schematic of the “L-H method” mining system; (b) Schematic diagram of drilling through the rock-bottom extraction roadway; (c) Schematic of gas control lane; (d) Drawing of gas drainage along the formation; (e) Schematic of gob-side entry; (f) Schematic of gas control lane in the lower section; (g) Schematic of gas control lane in the lower section.

The implementation is as follows:

① Analyze the geological conditions of the mining area, conduct a detailed investigation and research on the top and bottom conditions of the coal seam as well as the gas storage conditions and other mine information, and reasonably divide the working face of the mining area on the basis of the existing coal mine.

② Determine the location of the intermediate gas treatment lane at the first working face of the mining area, dig the bottom extraction lane in the rock of the bottom plate below for the inter-layer drilling operation, and design the inter-layer gas extraction parameters, as shown in Figure 1b.

③ The gas concentration in a certain area above can be reduced to the recoverable standard (below 8 m$^3$/t) by gas extraction through the layer and digging the intermediate gas control lane in the first mining face, as shown in Figure 1c.

④ Design the transport lane and the return air lane from the first mining face and design the layer-by-layer drilling gas extraction parameters according to the coal seam gas storage conditions, which will be implemented on the first mining face.

⑤ Use layer-by-layer drilling gas extraction to reduce the gas concentration in the design area of the transport lane and to return air lane to the recoverable standard. Dig into the transport lane of the first mining face and return air lane and open cuttings, as shown in Figure 1d.

⑥ The first mining face is retrieved, and the plan and process parameters of the first mining face are designed according to the conditions of the top and bottom of the coal seam and retained along the gob-side entry retention area of the first mining face, as shown in Figure 1e (red area is the gob-side entry retention).

⑦ Determine the location of the lower section of the gas control lane, and while digging the return air lane of the first mining face to the shallow coal body of the lower section, implement layer-by-layer drilling gas extraction (gas management equipment installation operations should be closely linked to roadway excavation operations), as shown in Figure 1f.

⑧ Excavate the lower section gas management lane and conduct down-seam gas extraction of the deep coal body in the lower section simultaneously.
Dig into the lower section of the return lane, open the cuttings, and when the first working face is completed, refurbish the roof-cutting and pressure-releasing roadway and carry out the next working face of the return mining work, as shown in Figure 1g.

Using the parity of reasoning, repeat 8–9 to complete the remaining working faces for the recovery work in the mining area.

The above steps are the main implementation process for the “L-H method”. This method is universally applicable to coal seams with gas prominence. It should be noted that when the technology becomes more mature, rock-bottom extraction can be avoided altogether. The gas can be unloaded by means of hydraulic fracturing, then digging the gas intermediate management tunnel of the first working face, and then digging the double tunnel of the first working face. The main deformation is the deformation of the filling body next to the alleyway in the vertical direction. The filling body has sufficient bearing and resistance to deformation and is the key to the success of the alleyway along the empty stay [18–20]. If the coal mine equipment conditions allow for the use of long drill holes for layer-by-layer gas extraction, in addition to digging into the gas intermediate alley of the first mining face, digging does not need to be carried out in the remaining mining faces.

2.2. Construction of “L-H Method” Mining Area Mining Model

The “L-H method” was proposed to solve the problem of high-volume rock roadway excavation in gas-emitting coal seams as well as insufficient gas extraction time and other problems related to the status quo. To this end, a complete set of technical methods for the safe and efficient mining of gas-accentuated coal seams is summarized, and a mining model is constructed to study the mining area. The working face markings in the mining area model are, from right to left, working face A, working face B . . . , working face N, and they assume consistent roadway boring standards in the mining area. Taking working face A as an example, the working face strike length is \( S \), the tendency length is \( L \), the coal seam height is \( H \), the width of the rock tunnel is \( l_1 \), and the height of the rock tunnel is \( h_1 \). As for the rock-bottom pumping lane, the length of the working face lane is the same. The rock-bottom extraction roadway is \( l_y \), the height is \( h_y \), the along-layer drilling length is \( l_s \), and the drill length through the layers is \( l_c \), and the mining area model is shown in Figure 2.

![Figure 2. Establishment of mining area model.](image)

2.2.1. New Calculation of the Mining Area Volume \( J \) for the “L-H Method”

\( J_y = l_y S h_y \)  

In the formula, \( J_y \) is the amount of rock roadway excavation, \( m^3 \); \( l_y \) is the width of the rock tunnel, m; \( S \) is the length of the rock tunnel, m; and \( h_y \) is the height of the rock tunnel, m.
“L-H method” drilling through the mining area $Z_c$

$$Z_c = kl_c \frac{S}{m}$$

In the formula, $Z_c$ is the amount of drilling work through the layers, m; $S$ is the length of the roadway, m; $l_c$ is the length of the drill hole through the layer, m; $m$ is the layer borehole spacing, m; and $k$ is the number of holes drilled in the roadway section.

In the “L-H method”, only one rock-bottom extraction road is dug at the first working face of the mining area, which greatly reduces the amount of rock-bottom road extraction required compared to the traditional gas-accentuated coal seam mining method. Compared to the traditional gas-accentuated coal seam method, it greatly reduces the amount of digging work required in the rock-bottom extraction lane. The traditional method for mining a coal seam with gas prominence requires digging two bottom extraction lanes in the first working face. This resulted in three rock-bottom extraction lanes serving two working faces in sequence. Therefore, the number of undercutting lanes was $N + 1$, which is $N$ more undercutting lanes than the “L-H method”, resulting in an extra $N J_y$ of rock tunneling work and an increase in the drilling work through the layers of $NZ_c$.

3. Quantity of coal seam roadway boring in the “L-H method” mining area $J_m$

$$J_m = (2N + 1)l_1sh_1 + J_{\text{open}}$$

In the formula, $N$ is the number of working surfaces; $J_m$ is the amount of coal tunneling work, m$^3$; $l_1$ is the width of the roadway, m; $S$ is the length of the roadway, m; $h_1$ is the height of the roadway, m; and $J$ is the amount of work required to open the cuttings, m$^3$.

4. Layer-by-layer drilling $Z_s$ in the “L-H method” mining area

$$Z_s = \frac{2S}{n} l_s N$$

In the formula, $N$ is the number of working surfaces; $Z_s$ is the amount of drilling work in the mining area, m$^3$; $l_s$ is the length of the borehole along the layer, m; $S$ is the length of the roadway, m; and $n$ is the drill spacing along the layer. In the “L-H method”, gas interlacing is located in the middle $\frac{S}{2}$ of the working face. The length of the layer-by-layer gas extraction borehole to the working face in the gas control lane should meet the following requirements: $0 m < l_s < \frac{L_2}{l_1}$. Compared to traditional mining methods for gas-accentuated coal seams, the amount of coal roadway boring work increased by one $l_1sh_1$, the same amount of drilling work in the cascade.

In summary, the total quantity of work in the “L-H method” mining area is the amount of rock roadway excavation plus the amount of through-seam drilling, the coal roadway excavation volume, and the down-hole drilling volume:

$$J_{\text{New}} = J_y + Z_c + J_m + Z_s$$

The total amount of work in the mining area under the conventional mining method for gas outburst in coal seams is

$$J_{\text{Trans}} = (N + 1)(J_y + Z_c) + 2Nl_1sh_1 + Z_s + J_{\text{open}}$$

The “L-H method” reduces the amount of work across the mining area compared to conventional mining methods by

$$J_{\text{New}} - J_{\text{Trans}} = N(J_y + Z_c) - l_1sh_1$$
2.2.2. Calculation of the Digging Time Required in the “L-H Method” Mining Area

To facilitate the calculation of the total digging time in the “L-H method” mining area, assuming that the mining area is equipped with only one digging team, the “L-H method” mining area roadway digging time $T_{New}$ is

$$T_{New} = (N + 1) \frac{S}{t_1} + N \frac{S}{t_2} + \frac{S}{t_3} + \frac{S}{t_4}$$  \hspace{1cm} (8)

In the formula, $T_s$ is the digging time of all of the roadways in the mining area, d; $N$ is the number of working surfaces; $S$ is the length of the tunnel, m; $t_1$ is the speed at which the workings are dug in the double lane, m/d; $t_2$ is the digging speed of gas intermediate control lane, m/d; $t_3$ is the speed of rock tunnel excavation, m/d; and $t_4$ is the opening speed of the cutting hole, m/d.

Under conventional mining methods in gas outburst coal seams, the mining time $T_{Trans}$ is

$$T_{Trans} = 2N \frac{S}{t_1} + (N + 1) \frac{S}{t_3} + \frac{S}{t_4}$$  \hspace{1cm} (9)

The “L-H method” reduces the preparation time for the entire mining area compared to conventional mining methods:

$$T_{Trans} - T_{New} = (N - 1) \frac{S}{t_1} - N \frac{S}{t_2} + N \frac{S}{t_3}$$  \hspace{1cm} (10)

The superiority of the “L-H method” was analyzed by building a model for mining gas-accentuated coal seams and was compared to conventional mining methods for gas-outburst coal seams. It was determined that the full mining area can reduce the $N (J_y + Z_c) - t_1 Sh_1$ quantity of work, saving $(N - 1) \frac{S}{t_1} - N \frac{S}{t_2} + N \frac{S}{t_3}$ preparation time.

3. Results and Analysis of Feasibility in the H Coal Mine

3.1. Analysis of Roadway Stability of Top-Cutting and Pressure-Relief Stay Roadway

According to the actual geological situation of H coal mine, this paper carries out a thorough study on the safe and efficient mining of coal seam resources with gas outburst by means of theoretical analysis, numerical simulations, and field tests, all of which were successfully verified in an H coal mine. Considering traditional coal seam mining with gas outburst, it is urgent to innovate technical methods to ensure that the technology is applicable, safe, and reliable and that the efficiency is improved. An H coal mine contains gas outburst coal seams, and until now, 24 coal and gas outburst disasters have occurred. Therefore, the safe and efficient mining of coal seam resources with gas outburst is a significant problem that needs to be solved, as shown in Table 1.

Roof cutting and pressure release without coal column mining technology refer to pre-cutting the roof plate on the side of the backwind lane of the working face to a certain distance in advance, so that the overlying rock layer in the mining area collapses under the action of the mine pressure according to the cuts and forms the roadway gang [21–23]. Additionally, by implementing blasting pre-cracking through the top plate, the association between the roof plate of the roadway and the overlying rock layer of the mining area is cut off to realize the transformation from a long-armed beam structure to a short-armed beam structure, which enhances the stability of the structure and fundamentally changes the stress distribution law of the surrounding rock along the empty roadway under the influence of mining motion [24,25]. In the process of automatic formation caused by roof cutting and pressure release, adjusting the roof structure will lead to a large amount of deformation, and the surrounding rock of the roadway will yield or even result in plastic flow, as the coal body is far from the free surface when it is still in its elastic state [26,27]. Therefore, FLAC3D (Fast Lagrangian Analysis of Continua) can better simulate the distribution of stress and strain in the surrounding rock of the roadway, which can help analyze the distribution...
and change law of stress and displacement in the surrounding rock of the roof-cutting and pressure-releasing automatic roadway [28–30].

### Table 1. Statistics of Coal and Gas Outburst in H Coal Mine.

<table>
<thead>
<tr>
<th>No.</th>
<th>Coal Seam</th>
<th>Prominent Location</th>
<th>Coal Outburst (t)</th>
<th>Gas Volume (m$^3$)</th>
<th>Operating Type</th>
<th>Field Geology</th>
<th>Elevation of Prominent Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9#</td>
<td>North return air lane</td>
<td>70</td>
<td>37,000</td>
<td>After the gun</td>
<td>Faults H = 1.0 m</td>
<td>+1047</td>
</tr>
<tr>
<td>2</td>
<td>9#</td>
<td>North transport lane</td>
<td>40</td>
<td>11,120</td>
<td>After the gun</td>
<td>Faults H = 0.7 m</td>
<td>+1041</td>
</tr>
<tr>
<td>3</td>
<td>9#</td>
<td>North transport lane</td>
<td>260</td>
<td>22,464</td>
<td>Coal loading after the gun</td>
<td>Faults H = 1.5 m</td>
<td>+1041</td>
</tr>
<tr>
<td>4</td>
<td>9#</td>
<td>South return air lane</td>
<td>80</td>
<td>15,882</td>
<td>After the gun</td>
<td>Faults H = 2 m</td>
<td>+1047</td>
</tr>
<tr>
<td>5</td>
<td>9#</td>
<td>Original 1293 lane</td>
<td>45</td>
<td>7920</td>
<td>After the gun</td>
<td>Faults H = 0.7 m</td>
<td>+1041</td>
</tr>
<tr>
<td>6</td>
<td>9#</td>
<td>Original 1293 lane</td>
<td>24</td>
<td>5700</td>
<td>After the gun</td>
<td>Faults H = 0.8 m</td>
<td>+1060</td>
</tr>
<tr>
<td>7</td>
<td>9#</td>
<td>Original 1293 lane</td>
<td>20</td>
<td>4700</td>
<td>Collect floating coal</td>
<td>Faults H = 0.8 m</td>
<td>+1061</td>
</tr>
<tr>
<td>8</td>
<td>9#</td>
<td>Original 1293 lane</td>
<td>40</td>
<td>10,700</td>
<td>After the gun</td>
<td>Faults H = 0.8 m</td>
<td>+1045</td>
</tr>
<tr>
<td>9</td>
<td>9#</td>
<td>Original 1293 wind lane</td>
<td>55</td>
<td>970</td>
<td>After the gun</td>
<td>Coal seam thickness variation</td>
<td>+1046</td>
</tr>
<tr>
<td>10</td>
<td>9#</td>
<td>North return air lane</td>
<td>102</td>
<td>28,356</td>
<td>After the gun</td>
<td>Faults H = 1.0 m</td>
<td>+1040</td>
</tr>
<tr>
<td>11</td>
<td>9#</td>
<td>North transport lane</td>
<td>108</td>
<td>2320</td>
<td>After the gun</td>
<td>Faults H = 0.4 m</td>
<td>+1048</td>
</tr>
<tr>
<td>12</td>
<td>5#</td>
<td>Shimen 1251</td>
<td>10</td>
<td>2432</td>
<td>After the gun</td>
<td>Faults H = 0.6 m</td>
<td>+1016</td>
</tr>
<tr>
<td>13</td>
<td>9#</td>
<td>Two mining areas’ transport up the mountain</td>
<td>31</td>
<td>587</td>
<td>Play for anchor</td>
<td>Faults H = 0.6 m</td>
<td>+1016</td>
</tr>
<tr>
<td>14</td>
<td>9#</td>
<td>Two mining areas’ transport up the mountain</td>
<td>18</td>
<td>795</td>
<td>Collect floating coal</td>
<td>Floppy right gang</td>
<td>+1007</td>
</tr>
<tr>
<td>15</td>
<td>9#</td>
<td>1293 shipping lane</td>
<td>27</td>
<td>3710</td>
<td>Collect floating coal</td>
<td>Faults H = 0.8 m</td>
<td>+1042</td>
</tr>
</tbody>
</table>

The geology parameters are based on Table 2 below.

### Table 2. Geology parameters.

<table>
<thead>
<tr>
<th>Name of Rock</th>
<th>Thickness/m</th>
<th>Density/kg·m$^{-3}$</th>
<th>Internal Friction Angle/°C</th>
<th>Bulk Modulus/Pa</th>
<th>Shear Elasticity/Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silty Mudstone</td>
<td>3.0</td>
<td>2570</td>
<td>37</td>
<td>$9.41 \times 10^9$</td>
<td>$5.56 \times 10^9$</td>
</tr>
<tr>
<td>Mudstone</td>
<td>4.0</td>
<td>2360</td>
<td>32</td>
<td>$7.28 \times 10^9$</td>
<td>$7.76 \times 10^9$</td>
</tr>
<tr>
<td>Limestone</td>
<td>1.0</td>
<td>2480</td>
<td>38</td>
<td>$8.91 \times 10^9$</td>
<td>$9.14 \times 10^9$</td>
</tr>
<tr>
<td>Siltstone</td>
<td>7.3–8.0</td>
<td>2570</td>
<td>41</td>
<td>$10.11 \times 10^9$</td>
<td>$10.89 \times 10^9$</td>
</tr>
<tr>
<td>Mudstone</td>
<td>6.27</td>
<td>2550</td>
<td>32</td>
<td>$7.09 \times 10^9$</td>
<td>$7.64 \times 10^9$</td>
</tr>
<tr>
<td>Micropsammite</td>
<td>3.0</td>
<td>2660</td>
<td>41</td>
<td>$7.67 \times 10^9$</td>
<td>$7.24 \times 10^9$</td>
</tr>
<tr>
<td>Siltstone</td>
<td>4.0</td>
<td>2530</td>
<td>44</td>
<td>$10.76 \times 10^9$</td>
<td>$10.36 \times 10^9$</td>
</tr>
<tr>
<td>Siltstone</td>
<td>1.9</td>
<td>2560</td>
<td>39</td>
<td>$10.51 \times 10^9$</td>
<td>$10.54 \times 10^9$</td>
</tr>
<tr>
<td>Dolomitized Tuff with Mudstone</td>
<td>3.0</td>
<td>2900</td>
<td>30</td>
<td>$8.19 \times 10^9$</td>
<td>$8.95 \times 10^9$</td>
</tr>
</tbody>
</table>

#### 3.1.1. Model Building

The model dimensions are as follows: length $\times$ width $\times$ height = 200 m $\times$ 200 m $\times$ 50 m; the size of the simulated tunnel excavation is 4 m $\times$ 200 m $\times$ 3.5 m; the simulated tunnel has a burial depth of 300 m, and the tunnel is dug along the top and bottom of the coal seam; the top slab is 3.0 m thick siltstone, 4.0 m thick mudstone, 1.0 m thick limestone, 7.3 m–8.0 m thick siltstone, 6.27 m thick mudstone, and 4.0 m thick micropsammite, in descending order. The bottom slab is 1.9 m thick siltstone and 3.0 m thick dolomitized tuff with mudstone from top to bottom. The calculation model is shown in Figure 3.

The left and right boundaries of the model restrict the displacement in the x direction, and the front and rear boundaries restrict the displacement in the y direction and apply the horizontal compressive stress with depth; the lower boundary restricts the displacement in the z direction, and the upper boundary applies the uniform self-weight stress.
3.1.2. Feasibility of surrounding rock control

This subsection simulates the surrounding rock deformation control effect implemented by the H coal mine due to roof cutting and pressure release along the gob-retaining roadway scheme using Flac3D numerical simulation software to verify the feasibility. After the top of the roadway is cut, the overlying rock layer in the mining area will sink due to its own excessive load, and various mechanical effects will be generated between the sinking process and the roadway roof, which will lead to the deformation of the roadway roof. FLAC3D was used to build a calculation model to simulate the stress and displacement distribution characteristics of the surrounding rock at a cutting angle of 15° and depth of 10 m. The calculation results are shown in Figure 4.

According to the vertical stress distribution diagram in Figure 4, after the excavation of the working face, the stress concentration area inside the solid coal gang of the 15° cut channel is about 5.0~6.0 m away from the channel gang, and the maximum vertical stress is 6.41 MPa; the pressure relief area above the channel and on the side of the hollow mining area is larger. According to the vertical displacement distribution diagram in Figure 4, the cut seam effectively cuts off the stress transfer between the channel and the roof plate of the hollow mining area and effectively controls the deformation of the channel. The maximum vertical displacement is 450 mm and is located at the side of the mining area.

In order to further illustrate the effect of roof cutting and pressure release along the gob-retaining roadway of the working face, the law of mineral pressure emergence during working face recovery process is analyzed; the distribution characteristics of the stress and displacement of the roadway-surrounding rock during the working face recovery process are studied; and the law of mineral pressure emergence during working face recovery is summarized. Numerical simulation software was used to analyze the stress

Figure 3. Numerical calculation model.

Figure 4. Vertical stress and displacement of 15° slit: (a) vertical stress distribution diagram; (b) vertical displacement distribution diagram.
and displacement distribution characteristics of the surrounding rock at different distances from the working face by excavating at steps of 10 m per step.

According to the vertical stress distribution diagram in Figure 5, the stress concentration inside the solid coal gang at 10 m in front of the working face is not obvious, and the maximum vertical stress is located inside the coal body in front of the working face; there is a pressure-relief area within a certain range above the roadway.

![Figure 5](image)

Figure 5. Vertical stress and displacement distribution at 10 m in front of the working face: (a) vertical stress distribution diagram; (b) vertical displacement distribution diagram.

According to the vertical displacement distribution diagram in Figure 5, the slit effectively cuts off the stress transfer between the roadway and the roof of the mining area, the deformation of the roof of the roadway is not large, and the maximum vertical displacement is located in the middle of the roadway.

According to the vertical stress distribution diagram in Figure 6, before the excavation of the working face, the stress inside the solid coal gang at 5 m in front of the working face is obvious. The maximum vertical stress is located inside the coal body in front of the working face; there is an unloading zone within a certain range above the roadway. There is an unloading area within a certain range above the roadway.

![Figure 6](image)

Figure 6. Distribution of vertical stress and vertical displacement at 5 m in front of the working face: (a) vertical stress distribution diagram; (b) vertical displacement distribution diagram.

According to the vertical displacement distribution diagram in Figure 6, the cutting slit effectively cuts off the stress transfer between the roadway and the roof of the mining area, and the deformation of the roof of the roadway is not large and is located in the middle of the roadway.
The following conclusions can be drawn by comparing the images in Figure 7:

1. In front of the working face, the stress concentration inside the coal gang of the roadway entity is not obvious, and the stress maximum is located in the roadway gang inside this working face.

2. After the working face is pushed through, the roof plate in the mining area collapses and sinks, and a low-stress area appears in a certain range; meanwhile, the stress concentration area appears inside the solid coal. At the same time, the stress concentration zone appears inside the solid coal gang, and with the continuous advancement of the working face, the stress concentration zone gradually shifts to the depth of the coal body.

![Figure 7](image_url)

**Figure 7.** (a) Vertical stress diagram at 15 m behind the working face; (b) vertical stress diagram at 25 m behind the working face; (c) vertical stress diagram at 40 m behind the working face; (d) vertical stress diagram at 50 m behind the working face.

The depth of the cutting seam was determined to be 10 m according to the rock fragmentation formula. On this basis, a numerical calculation model of an H coal mine was established, and the cutting seam angle and the law determining the appearance of mining pressure appearing during the roadway mining were analyzed to evaluate the roof-cutting and pressure-releasing technology implemented in the 20910 working face simulation and evaluation of the influence of roadway retention on the deformation of the surrounding rock of the roadway. This provides a theoretical basis for the implementation of roof-cutting and pressure-releasing technology.

### 3.2. Analysis of the Technical Effectiveness of Layer-by-Layer Gas Extraction

In the “Code of Practice for Coal Mine Gas Extraction” (AQ1027-2006) and the “Basic Indicators for Coal Mine Gas Extraction” (AQ1026-2006) as well as other relevant codes, it
is clearly stipulated that the gas concentration range must be controlled within 8 m$^3$/t or that the coal seam gas pressure must be reduced to 0.74 MPa (gauge pressure) or below. The 20912 header design has an average strike length of 850 m, an average inclination length of 175 m, and an average coal seam thickness of 3.3 m. The coal capacity is 1.53 t/m$^3$, and the coal reserve is 751,000 t. The gas content of the M9 coal seam is 23.42 m$^3$/t, and the gas reserve of the M9 coal seam in the 20912 header is calculated as follows:

$$75.1 \times 23.42 = 17,588,400 \text{ m}^3$$  \hspace{1cm} (11)

According to the “Basic Index of Coal Mine Gas Extraction” (AQ1026-2006) for gas-prominent coal seam extraction, the gas content should be reduced to below 8 m$^3$/t. The amount of gas to be extracted from the M9 seam for the 20912 headers to meet these requirements is as follows:

$$75.1 \times (23.42 - 8) = 1,158,000 \text{ m}^3$$  \hspace{1cm} (12)

It was calculated that at least 11.58 million m$^3$ of pre-pumped gas could be removed from this coal seam in the 20912 headers.

The gas content of the coal seam of the 20912 headers is 23.42 m$^3$/t; the coal density is 1.53 t/m$^3$; the moisture (Mad) is 4.46%; the ash (Ad) is 14.1%; the volatile content (Vdaf) is 6.2%; the amount of gas to be extracted from this coal seam of the mining face is 11,580,000 m$^3$; the extraction cycle is 60 days according to the pre-pumping calculations; the drilling distance is 3 m; and the extraction concentration was calculated to be 60%. In the return wind lane and gas management lane of each 20912 header, a gas extraction pipe was set up, and the extraction pre-pumping pure amount was determined to be

$$Q_{pure} = \frac{W_{should}}{24 \times 60 \times 60} = 134 \text{ (m}^3/\text{min})$$  \hspace{1cm} (13)

Single trip pipeline mixed extraction volume

$$Q = \frac{Q_{pure}}{60\%} \times \frac{1}{2} = 111.7 \text{ (m}^3/\text{min})$$  \hspace{1cm} (14)

Gas extraction pipe diameter

$$D = 0.1457 \sqrt{\frac{Q}{V}}$$  \hspace{1cm} (15)

In the formulae, $D$ is the inner diameter of the gas extraction pipe, m; $Q$ is the mixed gas flow rate of the extraction pipe, m$^3$/min; $V$ is the average flow rate of the extraction pipe, m/s; generally, this design takes 15 m/s. The inner diameter of the gas extraction pipe for cascade extraction can be calculated as

$$D = 0.1457 \sqrt{\frac{Q}{V}} = 0.1457 \sqrt{\frac{111.7}{15}} = 400 \text{ (mm)}$$  \hspace{1cm} (16)

In summary, after the completion of all of the extraction pipeline equipment, the 20912 working faces can be reduced to less than 8 m$^3$/t and meet the requirements for working face outburst prevention, achieving a 60% extraction concentration for 60 d. The length of the 20910 working face is 850 m, allowing two excavation teams to work simultaneously. After a double 20910 lane is dug out, digging can start for the 20912 gas control lane, and according to 5 m/d calculation, which can be dug out in 170 d (because the double lane of the 20910 working face is dug at the same time as the lower down layer extraction section, and the digging time is much longer than the 60 d required for extraction, so the 20910 double lane can be dug into the 20912 gas control lane directly after digging); after the excavation of the 20912 gas control roadway, the 20912 return air
roadway can begin to be excavated (since the strata drainage of the lower section can be carried out at the same time as the 20912 gas control roadway, and the excavation time is much longer than 60 d, the 20912 return air roadway can be directly excavated after the excavation of the 20912 gas control roadway). According to the 4 m/d calculation, the 20912 return airway can be dug out in 212.5 d, and the 20912 working roadway requires 382.5 d of digging. Based on the current 20910 working roadway recovery rate (average 3 m/d), the required time for the completion of 20910 roadway recovery and related work, such as moving equipment, is 298.3 d (the time required for working face moving is calculated to be 15 d). After moving the working face, the 20910 roadway was dismantled and refurbished (according to 8 m/d) in 106.25 d, requiring a total of 404.55 d. The above-mentioned 20912 gas control lane working face tunneling time was 170 d, and after the end of 20912 working face retrieval, the layer-by-layer drilling gas extraction of the 20912 working face cutting hole reached 234.55 d, meaning that it can carry out 20912 working face retrieval work directly. As such, the use of layer-by-layer drilling gas extraction can fully meet the requirements of 20912 working face mining succession work, proving its technical feasibility.

According to Table 3, the gas extraction amount of the 20910-mining face (20912 coal body side extraction amount) and the 20912 intermediate lane (20912 remaining coal body extraction from January 2019 to September 2020 is 14.9 mln m$^3$, which is 3.4 mln m$^3$ more than the 11.5 mln m$^3$ of gas required to meet the anti-surge extraction requirements of the H coal mine) [12].

Table 3. Gas drainage volume.

<table>
<thead>
<tr>
<th>Construction Location</th>
<th>Year</th>
<th>Month</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
<th>Total</th>
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<tbody>
<tr>
<td>20910 mining face</td>
<td>2019</td>
<td>3.28</td>
<td>6.56</td>
<td>6.20</td>
<td>10.02</td>
<td>39.71</td>
<td>39.71</td>
<td>56.21</td>
<td>46.88</td>
<td>51.32</td>
<td>48.08</td>
<td>42.77</td>
<td>66.54</td>
<td>442.1</td>
<td></td>
</tr>
<tr>
<td>20910 mining face</td>
<td>2020</td>
<td>62.73</td>
<td>25.77</td>
<td>36.57</td>
<td>40.58</td>
<td>36.23</td>
<td>27.81</td>
<td>26.21</td>
<td>14.55</td>
<td>9.95</td>
<td>20.3</td>
<td>41.9</td>
<td>47.5</td>
<td>47.5</td>
<td>40.1</td>
</tr>
<tr>
<td>20912 mining face</td>
<td>2019</td>
<td>20.3</td>
<td>41.9</td>
<td>47.5</td>
<td>47.5</td>
<td>9.95</td>
<td>20.3</td>
<td>41.9</td>
<td>47.5</td>
<td>47.5</td>
<td>47.5</td>
<td>47.5</td>
<td>57.33</td>
<td>95.69</td>
<td>309.9</td>
</tr>
<tr>
<td>20912 mining face</td>
<td>2020</td>
<td>65.52</td>
<td>57.33</td>
<td>68.79</td>
<td>65.52</td>
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<td>52.76</td>
<td>32.76</td>
<td>26.21</td>
<td>486.5</td>
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</tr>
</tbody>
</table>

4. Discussion

A numerical simulation of roadway stability was carried out based on roadway support and slit parameters. The technical feasibility of roof cutting along the gob-retaining roadway was discussed, and the feasibility of layer-by-layer drilling gas extraction was studied according to theoretical calculations. The numerical simulation shows that the stress concentration zone gradually shifted to the depth of the coal body, as back mining advanced in the 20910 working face of the H coal mine, and that the pressure-relief zone existed within a certain range above the roadway, indicating that the use of roof cutting and pressure release along the gob-retaining roadway can effectively cut off the connection between the roof of the roadway and the overburden of the mining area, control roadway deformation, and realize the real meaning of gob-side entry retention.

According to the model solution, when the first working face is being re-mined, the use of down-seam drilling gas extraction can fully meet the conditions of the re-mining work in the next working face and achieve the successful mining work on the basis of engineering volume savings. The down-seam drilling gas extraction method only includes drilling in this coal seam and avoids digging into the rocky roadway at the bottom, which greatly reduces the amount of roadway digging work and the pressure upon the completion of roadway digging. Therefore, the gas extraction rate can be improved by providing reasonable drilling spacing (effective radius of extraction) and the selection of suitable negative pressure and drilling length. The down-hole drilling gas extraction method adopts extraction while digging and extraction during the implementation of other mining methods, i.e., the gas is pre-pumped to the next mining face coal seam when the tunnel is being dug, and the gas is extracted and released during the working face recovery process. This guarantees that the gas extraction time requirements for surface mining reduce the frequency of gas overruns at the working face and ensure safety.
The two core technologies of the “L-H method” are top-cutting and pressure-relieving along-airway technologies and layer-by-layer drilling gas extraction, which can provide technical support for the safe and efficient mining of gas-accentuated coal seams and are feasible according to the practical results obtained from coal mines. However, there are still several shortcomings. On the one hand, these two technologies were applied to H coal mines and achieved good results, but a number of coal mines have not been verified, so the use of these technologies lacks practical support. On the other hand, the “L-H method” is less labor intensive and shorter than conventional methods, which will reduce the costs and increase the benefits. However, this paper lacks a complete economic analysis and evaluation of the technology, which makes the evaluation of the two technologies in the whole gas-accentuated coal seam mining life cycle incomplete, and this needs to be improved and organized in further research.

5. Conclusions

The green mining system known as the “L-H method” proposed in this paper completely solves the problem of safe and efficient H coal seams with gas outburst mining, improves the safe and green production level of the mine, and has application value. Compared to the conditions of similar gas outburst coal seam mining methods, we provide a mining method that can not only relieve the tension of mining continuity in the coal face, improve the recovery rate of coal resources, and maintain the stability of the rock surrounding the roadway, but it can also greatly reduce the amount of tunneling in the rock roadway. Reducing the cost of tons of coal to produce huge economic benefits will increase the popularization value. The main conclusions can be summarized as follows:

(1) The “L-H method” is proposed, and a mining process for gas-accentuated coal seams is described in detail by establishing a gas-accentuated coal seam mining model, and the superiority of the “L-H method” technical system is illustrated more visually.

(2) For the H coal mine, the stability of the retention lane was simulated, and it was verified that the use of top-cutting and pressure-removal technology was feasible; the deformation of the surrounding rock was effectively controlled, and the real sense of gob-side entry retention was realized.

(3) Analyzing the characteristics of the coal seam gas deposit, this paper designed a gas extraction plan for the down-seam borehole of the 20912 working face. Under the conditions of meeting the set parameters, the gas extracted from the down-seam borehole meets the anti-surge requirements of the working face before the recovery of the 20912 working face, making it technically feasible.

(4) Through the verification of the “L-H method” mining technology in the two coal seam mining areas in an H coal mine, the applicability of the “L-H method” to coal seams with gas outburst was proved, and the purpose of technical applicability, safety, and reliability was achieved.

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