Research Article

Numerical and Similarity Simulation Study on the Protection Effect of Composite Protective Layer Mining with Gently Inclined Thick Coal Seam

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Protective layer mining, as a dominating method for preventing coal and gas outburst, is generally adopted in highly gassy coal mines. In the absence of a suitable thickness coal seam to serve as the protective layer, the rock-coal composite protective layer was proposed in this paper. We conducted a series of simulations and engineering measurements to investigate the protective effect under the mining of the rock-coal composite protective layer of the Zhongtai coal mine located in the Hebi area of Henan, China. The numerical simulation analysis showed that, after the completion of protective layer mining, the minimum vertical stress of the No. 2-1 coal seam had been reduced to 3.46 MPa. The maximum vertical displacement of the No. 2-1 coal seam is 455.01 mm. The maximum expansion deformation of the No. 2-1 coal seam is 9.77‰; the effective pressure relief range is as long as 160 m. The similarity simulation experiment revealed that, after the completion of protective layer mining, the minimum vertical stress of the No. 2-1 coal seam is 4.0 MPa. The maximum vertical displacement of the No. 2-1 coal seam is 640 mm. The maximum expansion deformation of the No. 2-1 coal seam is 26.37‰; the effective protection range reaches 130 m. The engineering measurements demonstrated that the variation law of gas drainage parameters in the protected layer corresponds to the protected layer’s vertical stress distribution law in numerical simulation and similarity simulation. With the exploitation of the composite protective layer, the protective layer’s pressure begins to release. The average gas drainage concentration is 2-3 times of that before the composite protective layer mining.

1. Introduction

China’s coal production accounts for 70% of the nation’s total energy supply and accounts for 85% of the world’s coal production [1, 2]. Coal mine gas (CMG) (mainly methane) produced during coal mining is considered clean energy in recent years [3, 4]. However, coal mine gas is also deemed as a major threat to the safety of coal mine [5, 6]. Currently, coal and gas outburst mines still occupy a large proportion of China’s production and under construction mines. From 2013 to 2017, the coal mine accidents in China caused by gas accounted for 11.21% of the total accidents [7].

With the depletion of shallow coal resources, the mining depth of coal mine is increasing. It is estimated that the mining depth will reach 1500 m in the next 20 years [8, 9]. The Earth stress, gas pressure, and gas content increase with the mining depth, and the surrounding rock shows large and long-term deformation under the large Earth stress [10–13]. Simultaneously, the coal seams’ permeability decreases, making it more difficult to control and exploit coal mine gas effectively, leading to an increase in gas accident rate [14, 15]. The prevention and control measures of coal and gas outbursts are divided into regional outbursts’ prevention measures and local outbursts’ prevention measures. The
regional outburst prevention measures include protective layer mining and hydraulic fracturing. The local gas outburst prevention measures include loose blasting, hydraulic punching, and drainage drilling [16–19]. The protective layer mining technology has been verified as a constructive measure for preventing coal and gas disasters in the highly gassy coal mine [20, 21].

As depicted in Figure 1, the protective layer mining is to first mine the coal seam with low risk as to the protective layer, and the coal seam with high risk is the protected layer. In the protective layer mining, the overlying strata’s vertical cracks develop, forming a gas transportation channel, and a large amount of gas and water from the adjacent rock strata accumulate in the goaf. The protected layer’s gas pressure and Earth stress are released to reduce or eliminate the coal and gas outburst risk [22–24].

Many studies of the protective layer have been conducted based on the field test and numerical and similarity simulations to investigate the protective effect [3, 25–27]. Wang et al. [28] carried out a series of field tests to investigate the vertical displacement of the protected layer and obtained that the maximum vertical displacement of the protected layer was 13 mm. Fang et al. [29] studied the stress and deformation evolution law of the protected layer during the protective layer mining with a different inclination. They found that the deformation and failure of the protected layer decreased with the increased dip inclination of the protective layer. Yuan et al. [30] researched the protection effect of steeply incliner upper protective layer mining with different interlayer distances and discovered that the protection range was reduced with increased interlayer distance. Tu and Cheng [31] analyzed the protection effect of the remote upper protective layer mining by using Flac3D software. They indicated that the stress and gas pressure of the protected coal seam decreased significantly with the remote upper protective layer mining. Cao et al. [32] simulated the stress and displacement field of the protected layer under the lower protective coal seam mining. They acquired the evolution law of the stress and displacement field of the protected layer. Zhang et al. [33] simulated the evolution of the protected coal seam permeability under the different protective coal mining thicknesses in Huainan and Handeng mining areas by using the stress-damage-seepage coupling model. Cheng et al. [34] proposed an innovative technology using the soft rock as the protective seam in the absence of an appropriate coal seam. They analyzed the impacts of different mining parameters of the soft-rock protective seam on the pressure relief effect of the protected coal seam were through numerical simulation.

However, these studies mainly focus on the single coal seam or rock layer as the protective layer. Unfortunately, in practical engineering, the geological conditions are complex, and the thickness of a single rock or coal layer may not meet the needs of protective layer mining. Therefore, to achieve the protective effect of the protective layer mining, a rock-coal composite protective layer mining method was built. The rock-coal composite protective layer mining is different from single coal seam or rock stratum protective layer mining. The physical and mechanical properties of a single coal seam or rock stratum protective layer are relatively uniform. However, the physical and mechanical properties of the rock-coal composite protective layer are complex. It is necessary to explore the protective effect and mechanical evolution law of the protected layer under the rock-coal composite protective layer mining.

In this work, we take the rock-coal composite protective layer mining practice in the Zhongtai coal mine as a typical case. The numerical method, combined with the similarity simulation experiment, was used to investigate the protective effect of composite protective layer mining with gently inclined thick coal seam. The vertical stress, vertical displacement, expansion deformation, and fracture characteristics evolution law of the protected layer with the mining of the rock-coal composite protective layer were obtained. Then, the engineering measurements were adopted to verify the effect of composite protective layer mining. In the sections below, engineering background is presented in Section 2, numerical simulation is employed in Section 3, similarity simulation is applied in Section 4, engineering measurements are verified in Section 5, and summary and conclusion are provided in Section 6.

2. Engineering Background

The Zhongtai coal mine district is located in Hebi city, Henan province, China. The location map of the Zhongtai coal mine is shown in Figure 2(a). There are fifteen coal seams in the Zhongtai mining district, of which the No. 2-1 coal seam is the main mining seam. No. 2-1 coal seam is located in the lower part of Shanxi formation of the Permian system, with a stable occurrence and simple structure. The thickness of the No. 2-1 coal seam is 4.0 m-15.0 m, and the average thickness is about 7.3 m. The No. 2-1 coal seam in the mining district is gently inclined with a dip angle of 5°–25° and an average angle of 20°. The gas content of the No. 2-1 coal seam is 15.8 m³/t-20.8 m³/t, the gas pressure is 0.73 MPa–2.13 MPa, and the permeability coefficient is 0.03 mD–0.045 mD, which poses a danger of gas-burst potential. Due to the soft and broken coal seam, the drilling hole collapse is severe, and the construction of drainage drilling is difficult. The average depth of the drilling hole is only 60 m, which is a challenge to meet the extraction requirements. Moreover, the permeability of the coal seam is
low, the drainage effect is not perfect, the drainage rate is low, and the monthly progress of coal roadway excavation is less than 30 m. Therefore, it is decided to adopt the method of mining the protective layer to eliminate the threat of gas to the No. 2-1 coal seam and improve production efficiency.

The geological synthesis columnar of the case study mine and the mechanical parameters for the prototype coal-rock seam, which were obtained from geological reports, are shown in Figure 2(b) and Table 1. About 38.3 m below the floor of No. 2-1 coal seam is No.1-9 coal seam with an average thickness of 0.3 m. The roof of the No. 1-9 coal seam is limestone with a thickness of 4.5 m. About 41.0–44.0 m below the floor of No. 2-1 coal seam is No. 1-8 coal seam with a thickness of 0.2–0.9 m, with an average thickness of 0.6 m. The roof of the No. 1-8 coal seam is sandy mudstone with a thickness of 3.0 m–5.0 m, which is relatively broken and difficult to support.
The mining thickness of the protective layer directly affects the damage degree and height of the protected layer. The larger the mining thickness of the protective layer is, the larger the subsidence and expansion deformation rate of the protected layer are, which is beneficial to the gas pressure relief of the protected layer. However, suppose the mining thickness of the protective layer is too large. In that case, the mining conditions of the protected layer will be destroyed during the mining process of the protective layer, which will lose the significance of protective layer mining. The minimum requirement for the protective layer to have a protective effect is that the mining thickness of the protective layer should be greater than the overall deformation of the surrounding overlying rock. Suppose the mining thickness of the protective layer is too thin. In that case, the roof is automatically compacted and filled by the overlying strata, which shortens the closing period of the roof and floor of the goaf, shortens the pressure relief period of the protected layer, and reduces the protective effect of the protected layer. At this time, the protective effect of the protective layer on the protected layer is not apparent.

At present, the minimum effective thickness of lower protective layer mining can be determined by experience. The buried depth of No. 1-9 coal seam is 590 m–635 m and that of No. 1-8 coal seam is 593 m–641 m. When the working face width of the protective layer is 100 m–200 m, the minimum effective mining thickness of the lower protective layer is about 0.35 m–0.6 m. According to the "Provisions of the Prevention of Coal and Gas Outburst" [35], the maximum interval between the protective layer and the protected layer of gently inclined coal seam should be less than 100 m, and the minimum interval should be determined by

\[ H = K \cdot M \cdot \cos \alpha, \]

where \( H \) is the minimum interval between the protective layer and the protected layer, \( m \) is the roof management coefficient, \( K \) is taken as 10, \( M \) is the mining thickness of the protective layer, \( m \), and \( \alpha \) is the dip angle of the coal seam, \(^\circ\).

The distance from No. 1-8 coal seam and No. 1-9 coal seam to No. 2-1 coal seam 21 meets the requirements. According to equation (1), when the distance between the protective layer and the protected layer is about 40 m, the maximum mining thickness of the protective layer is about 4.26 m.

Limited by mining technology and combined with the existing mining equipment of Hebi Zhongtai Mining Co., Ltd, it is determined that the No. 1-9 coal seam is mined as a protective layer. The design thickness of the protective layer is 1.5 m, including No. 1-9 coal seam with a thickness of 0.3 m, and the sandy mudstone is located on the floor of the No. 1-9 coal seam with a thickness of 1.2 m, forming the rock-coal composite protective layer.

The rock-coal composite protective layer working face 3307B is located in the third level mining area of the Hebi Zhongtai coal mine. The comprehensive mechanized mining method of inclined mining is adopted in the 3307B working face. The buried depth of the working face is 628.2 m, the roof elevation is from −402.5 m to −446.5 m, the dip length is 248.0 m–271.5 m, and the strike length is 106.0 m.

| Lithology            | Compressive strength (MPa) | Cohesion (MPa) | Friction angle (°) | Poisson’s ratio | Elastic modulus (GPa) |
|----------------------|-----------------------------|----------------|-------------------|-----------------|-----------------------|
| Sandy mudstone       | 11.56                       | 3.71           | 24.6              | 0.31            | 1.57                  |
| Medium-course sandstone | 20.17                     | 6.35           | 25.6              | 0.27            | 1.23                  |
| Sandy mudstone       | 11.56                       | 3.71           | 24.6              | 0.31            | 1.57                  |
| Medium-course sandstone | 20.17                     | 6.35           | 25.6              | 0.27            | 1.23                  |
| Sandy mudstone       | 11.56                       | 3.71           | 24.6              | 0.31            | 1.57                  |
| Medium-course sandstone | 20.17                     | 6.35           | 25.6              | 0.27            | 1.23                  |
| Mudstone             | 6.27                        | 2              | 24.9              | 0.14            | 1.07                  |
| No. 2-1 coal seam    | 3.8                         | 1.27           | 22.3              | 0.21            | 0.86                  |
| Sandy mudstone       | 11.56                       | 3.71           | 24.6              | 0.31            | 1.57                  |
| Medium-course sandstone | 20.17                     | 6.35           | 25.6              | 0.27            | 1.23                  |
| Sandy mudstone       | 11.56                       | 3.71           | 24.6              | 0.31            | 1.57                  |
| Medium-course sandstone | 20.17                     | 6.35           | 25.6              | 0.27            | 1.23                  |
| Limestone 2          | 64.97                       | 17.97          | 32.1              | 0.2             | 6.05                  |
| No. 1-7 coal seam    | 3.04                        | 1.02           | 22.3              | 0.21            | 0.86                  |
| Sandy mudstone       | 7.17                        | 2.3            | 24.6              | 0.31            | 1.57                  |
| Medium-course sandstone | 20.17                     | 6.35           | 25.6              | 0.27            | 1.23                  |
| Sandy mudstone       | 11.56                       | 3.71           | 24.6              | 0.31            | 1.57                  |
| Medium-course sandstone | 20.17                     | 6.35           | 25.6              | 0.27            | 1.23                  |
| Limestone 1          | 64.97                       | 17.97          | 32.1              | 0.2             | 6.05                  |
| 3307B protective layer | 11.56                      | 3.71           | 24.6              | 0.31            | 1.57                  |
| Sandy mudstone       | 11.56                       | 3.71           | 24.6              | 0.31            | 1.57                  |
| No. 1-8 coal seam    | 3.8                         | 1.27           | 22.3              | 0.21            | 0.86                  |
| Medium-course sandstone | 20.17                     | 6.35           | 25.6              | 0.27            | 1.23                  |
| Sandy mudstone       | 11.56                       | 3.71           | 24.6              | 0.31            | 1.57                  |
| Limestone            | 64.97                       | 17.97          | 32.1              | 0.2             | 6.05                  |
| Sandy mudstone       | 11.56                       | 3.71           | 24.6              | 0.31            | 1.57                  |
3. Numerical Simulation

3.1. Numerical Model. According to the actual geological conditions of 3307B working face in the Zhongtai coal mine, Flac3D software is used to simulate the mining of the rock-coal composite protective layer, as shown in Figure 3. The inclined length of the model is 400 m. The strike length is 300 m; the vertical height is 136 m. The mining thickness of the protective layer is 1.5 m, the average thickness of the protected layer is 7.3 m, and the interval between the two layers is 38.3 m. The zero displacement boundary condition is adopted in the boundary of the model. The X, Y, and bottom directions are fixed, respectively; only the upper boundary can be moved and is a free boundary. The overlying strata are applied to the upper boundary of the model as external load and the external load $\sigma_0$ is 13 MPa. The Mohr–Coulomb model is used in the model structure, and the physical and mechanical parameters to be assigned are elastic modulus, cohesion, compressive strength, friction angle, etc. The values in Table 1 are used for the physical and mechanical parameters of coal-rock seams in the model. The large deformation method is used to deal with goaf in the process of simulation.

3.2. Results of the Numerical Simulation

3.2.1. Stress and Displacement Evolution. When the rock-coal composite protective working face is advanced to 40 m, 80 m, 120 m, 160 m, and 200 m, the vertical stress and displacement evolution law of the protected layer are shown in Figures 4–7.

As shown in Figures 4 and 5, when the 3307B working face is advanced to 40 m, the initial weighting of the roof occurred. At this time, the vertical stress of the No. 2-1 coal seam was 10.70 MPa–13.60 MPa, which had little change compared with the original rock stress, showing a weak pressure relief effect. When the working face is advanced to 80 m, the pressure relief effect is gradually apparent. The minimum vertical stress of the protected layer is reduced to 6.50 MPa, and the stress curve presents a “U” shape, and a stress reduction area appears. When the 3307B working face is advanced to 120 m, the minimum vertical stress is reduced to 4.19 MPa. The range of stress reduction in the goaf is continuously expanded, and the pressure relief effect is remarkable. When 3307 B working face is advanced to 160 m, the stress rose in the middle of the goaf, indicating that the goaf was continuously compacted. At this time, the minimum stress of the No. 2-1 coal seam is 3.90 MPa, the concentrated stress in front of the working face reaches 16.02 MPa, the stress curve of the protected layer presents a “W” shape, and the stress reduction area is further expanded. When the 3307B working face is advanced to 200 m, the minimum vertical stress of the protected layer has been reduced to 3.46 MPa.

As shown in Figures 6 and 7, when the 3307B working face is advanced to 40 m, the overburden strata subsided by self-weight, but the maximum subsidence value of No. 2-1 coal seam was only 49.71 mm, and the change was not noticeable. When the working face is advanced to 80 m, the height and width of the fracture zone continue to expand. The maximum subsidence value of the No. 2-1 coal seam reaches 153.70 mm, and the movement and deformation of the protected layer are massive. When 3307 B working face is advanced to 120 m, 160 m, and 200 m, the No. 2-1 coal seam continuously sinks with the continuous advance of the working face. The maximum subsidence displacement reaches 272.1 mm, 369.2 mm, and 455.01 mm, respectively.

3.2.2. Expansion Deformation Changes. The expansion deformation of the protected layer can be calculated by

$$F = \frac{s_1 - s_2}{h},$$

where $F$ is the expansion deformation, $s_1$ is the vertical displacement of the roof of the protected layer, $s_2$ is the vertical displacement of the protected layer floor, mm, $h$ is the thickness of the protected layer, mm.

When the protective working face is advanced to 40 m, 80 m, 120 m, 160 m, and 200 m, the expansion deformation changes of the protected layer is shown in Figure 8.

As depicted in Figure 8, when the 3307B working face is advanced to 40 m, the expansion deformation rate of the No. 2-1 coal seam reaches 0.10‰–1.61‰. The negative value of the expansion deformation rate appears near the front of the working face, which indicates that the front support pressure has an extrusion effect on the protected layer. When the working face is advanced to 80 m, the fracture zone gradually develops upward. The expansion deformation of the protected layer is more than 3‰ in some regions, which meets the critical value requirements of the “Provisions of the Prevention of Coal and Gas Outburst” [35]. When the 3307B working face is advanced to 120 m, with the gradual compaction of the goaf and the slow subsidence of overlying strata, the expansion deformation rate of the middle area of the protected layer tends to be stable and decreases. The expansion deformation rate is 6‰–8‰ in the middle of the goaf. When the working face is advanced to 160 m, the expansion deformation range of the protected layer increases, and the curve presents an “M” shape. When the 3307B working face is advanced to 200 m, the scope of the gradually compacted area behind the goaf was expanded. The maximum expansion deformation of the No. 2-1 coal seam reached 9.77‰. It shows that the pressure relief of the coal body is sufficient, and fracture development is perfect. The purpose of protective layer mining is achieved, providing ideal conditions for pressure relief gas drainage.

According to the requirements of “Provisions of the Prevention of Coal and Gas Outburst” [35], the expansion deformation of the protected layer should not be less than 3% to ensure the effect of pressure relief gas drainage. Considering that the permeability coefficient of the No. 2-1 coal seam in the studied mining area is low, it is difficult to extract gas from the No. 2-1 coal seam. For the sake of safety, the expansion rate of 5% is determined as the critical value to determine the pressure relief range. When the 3307B working face is advanced to 200 m, the range of expansion
deformation greater than 5% is selected as the pressure relief range. The length of the pressure relief range is about 160 m after calculation.

4. Physical Material Similarity Simulation Experiment

4.1. Similarity Condition and Similarity Material. In a similarity simulation model, the dip angle of the coal stratum is 8° and the inclined length of the coal seam is 2.524 m. There are 0.25 m length protective coal pillars on both sides of the rock-coal composite protective layer. The geometric similarity ratio of the model is 1:80, the bulk density similarity ratio is 0.6, the strength similarity ratio is 0.0075, and the time similarity constant is 0.1. Calcium carbonate, sand, gypsum, and water are used to simulate the rock layers, and mica powder is used to simulate the interface of the strata. The physical and mechanical properties of the similarity materials are listed in Table 2.

4.2. Experimental Procedure. Figure 9 shows the self-weight stress of overlying strata is provided by 14 hydraulic cylinders above the model. The average load of each hydraulic cylinder is 3482.1 N, and the total loading pressure is 1.1 MPa. The loading method is to pressurize from 0.5 MPa to 0.8 MPa, then to 1.1 MPa slowly, and then keep the stress at 1.1 MPa. The working face of the rock-coal composite protective layer adopts inclined mining, with 25 cm protective coal pillars reserved at both ends of the working face, and the working face is excavated from left to right. Each excavation length of the model is 10.1 cm. Eleven pressure sensors with a spacing of 20 cm were embedded in the roof of the No. 2-1 coal seam to monitor the pressure changes in the model. GPT-3102N total station is used to collect the vertical displacement of the overlying strata. It is located directly in front of the experimental model. The full caving method is used to deal with the goaf in the process of simulation.

4.3. Results of the Similarity Simulation

4.3.1. Fracture Characteristics. Figure 10 shows the fracture characteristics of the overlying strata while mining the rock-coal composite protective layer.

As shown in Figure 10, when the working face is advanced to 32.4 m, the initial weighting occurs on the roof, and it is broken into three pieces. The length of the cantilever beam at the open-off cut hole and the working face is 10 m and 9.6 m. The roof and the overlying strata have large separation fractures, and the fractures do not continue to develop upward. The sandy mudstone layer carries the load of the overlying strata. When the working face is advanced to 48.5 m, the straight cantilever beam is formed in the goaf behind the working face, and the roof separation fractures further developed upward. When the working face is advanced to 72.8 m, the overburden fracture develops to the No. 2-1 coal seam. The lower part of the protected layer is affected by mining, and the upper part remains intact. The height of the fracture development reaches 43.6 m, and the influence range reaches 28.6 m. The protected layer begins to expand and deform. At this time, a gas migration channel between the protected layer and the protective layer is formed, and a large amount of gas begins to flow to the goaf of the protective layer. When the working face is advanced to 84 m, vertical cracks appear in No. 2-1 coal seam and gradually expand and deform to form cracks and channels. The gas content and gas pressure of the No. 2-1 coal seam begin to release and decrease gradually. When the working face is advanced to 115.2 m, the fissures of the strata above the No. 2-1 coal seam are closed, and the whole rock strata have weak bending subsidence. With the continuous advance of the working face, the overlying strata move periodically, showing the coal wall support area, separation area, and re-compaction area. When the working face is advanced to 160 m, the fracture developed range reaches 110 m. The pressure relief angle of the downhill is 68° and that of the uphill is 55°. No. 2-1 coal seam is located at the boundary of the bending zone, and the fracture zone, combined with
pressure relief gas drainage, can reasonably achieve the purpose of gas release.

4.3.2. Stress and Displacement Evolution of the Overlying Strata. The vertical stress and vertical displacement of the experimental model were measured by pressure sensors and total station, respectively, as shown in Figures 11 and 12.

Figure 11 shows that when the working face is advanced to 32 m, the minimum vertical stress of the No. 2-1 coal seam is about 12.20 MPa, which is close to the original rock stress. When the working face is advanced to 64 m, the minimum vertical stress of the No. 2-1 coal seam is about 8.8 MPa, and the pressure relief phenomenon occurs. The stress concentration appeared at 32 m in front of the working face, and the stress concentration value reached 14.02 MPa. When the working face is advanced to 96 m, the minimum vertical stress of the No. 2-1 coal seam is about 5.5 MPa, and the pressure relief effect is remarkable. The stress concentration appeared at 32 m in front of the working face, and the stress concentration value reached 14.73 MPa. When the working face is advanced to 128 m, the minimum vertical stress of the

![Figure 4: Vertical stress distribution along the inclined direction in the mining of the rock-coal composite protective layer. (a) Working face is advanced to 40 m; (b) working face is advanced to 120 m; (c) working face is advanced to 200 m.](image-url)
Figure 5: Vertical stress curve for the No. 2-1 coal seam in the mining of the rock-coal composite protective layer.

Figure 6: Continued.
No. 2-1 coal seam is about 4.8 MPa. When the working face is advanced to 160 m, the minimum vertical stress of the No. 2-1 coal seam is about 4.0 MPa.

Figure 12 shows that when the working face is advanced to 32 m, the vertical displacement of limestone layer 1 is 1480 mm, and the vertical displacement is close to the mining height. No. 2-1 coal seam begins to deform, and the vertical displacement of the No. 2-1 coal seam floor is 480 mm. When the working face is advanced from 32 m to 112 m, the vertical displacement curve of each rock stratum is an approximately straight line. The vertical displacement of limestone layer 1 is about 1500 mm. The vertical displacement of limestone layer 2 is stable around 1250 mm. The vertical displacement of sandy mudstone is 1000 mm, and the vertical displacement of the floor of the No. 2-1 coal seam is 640 mm. When the working face is advanced from 112 m to 160 m, the vertical displacement of strata gradually slows down due to the influence of coal seam dip angle and mining height.

The expansion deformation changes in the protected layer are shown in Figure 13.

Figure 13 depicted that the expansion deformation changes’ curve increases firstly and then decreases with the advancing of the working face and shows a “Π” shape. When the working face is advanced from 12 m to 142 m, the maximum expansion deformation rate reaches 26.37 ‰, which is far greater than the specified index of 3 ‰. Take 5 ‰ as the critical value, the pressure relief range is 130 m, and the protective effect is obvious.

The vertical stress, vertical displacement, and expansion deformation evolution law of the protected layer of the numerical method and the similarity simulation experiment are similar. The minimum vertical stress of the No. 2-1 coal

\[
\begin{align*}
\text{Vertical stress (MPa)} & \quad \text{Vertical displacement (mm)} \\
\text{Distance from the open-off cut along the mining direction (m)} & \quad 40 m \quad 80 m \quad 120 m \quad 160 m \quad 200 m \\
\end{align*}
\]

\[
\begin{align*}
\text{Expansion deformation (‰)} & \quad \text{Distance from the open-off cut along the mining direction (m)} \\
\text{Distance from the open-off cut along the mining direction (m)} & \quad 40 m \quad 80 m \quad 120 m \quad 160 m \quad 200 m \\
\end{align*}
\]
seam decreases with the advance of the working face. The maximum subsidence value of the overlying strata increases with the advance of the working face. The expansion deformation rate of the protected layer increases with the advance of the working face. With the exploitation of the protective layer, the pressure of the protected layer begins to release, and the pressure relief range is expanded.

5. Engineering Measurements

During the mining process of 3307B composite protective layer working face in the Zhongtaic coal mine, the monitoring system was arranged in the bottom drainage roadway to measure the gas concentration and gas content of the main drainage pipe. The influence of the composite protective layer mining process on the gas drainage effect is evaluated. The variation law of extraction parameters of the main drainage pipe in the 3070B bottom drainage roadway is shown in Figure 14.

Figure 14 depicted that when the 3307B working face advanced from 0 m to 47 m, the gas concentration is less than 10%, and the mixture and purity gas drainage content is zero. When the 3307B working face is advanced from 48 m to 84 m, the gas concentration is between 4% and 28% and the maximum mixture and purity gas content is 18 m³/min and 4.8 m³/min, respectively. When the 3307B working face advanced from 85 m to 119 m, due to the opening of the airtight door in the bottom drainage roadway, the gas is gradually discharged, the gas concentration is below 4%, and the gas content is close to zero. When the 3307B working face advanced from 120 m to 129 m, the maximum gas concentration is 26%. Most of the mixture gas content is above 10 m³/min, the maximum mixture gas content is 57 m³/min, the purity gas content is more than 4 m³/min, and the maximum purity gas content is 14 m³/min. When the 3307B working face advanced from 130 m to 132 m, the gas concentration is 12%–26%, the mixture gas content is 30 m³/min–50 m³/min, and the purity gas content is 8 m³/min–13 m³/min. When the 3307B working face advanced from 133 m to 148 m, the gas concentration is between 13.41% and 23.75%. The mixture gas content is stable at about 25 m³/min, and the purity gas content is 4 m³/min–6 m³/min. When the 3307B working face advanced from 149 m to 193 m, the gas drainage concentration is between 4% and 27%. The mixture gas content is stable in the range of 27 m³/min–29 m³/min, and the purity gas content fluctuates around 7 m³/min. When the 3307B working face advanced from 194 m to 201 m, the gas drainage system failed to record the extraction parameters effectively, and all the gas drainage parameters become smaller. When the 3307B working face is advanced from 202 m to 240 m, the gas concentration increased again, the maximum gas concentration is 49.3%, the maximum mixture gas content is 34.1 m³/min, and the maximum purity gas content is 15.6 m³/min.

The variation law of gas drainage parameters in the protected layer corresponds to the vertical stress distribution law of the protected layer in numerical simulation and similarity simulation. The average gas drainage concentration of the protected layer is about 10% when the protective layer is not affected by the mining of the protective layer. With the exploitation of the protective layer, the pressure of the protected layer begins to release. The permeability of the coal seam increases, and the average gas drainage concentration reaches 20%–30%, which is 2-3 times before the protective layer mining.

### Table 2: Physical and mechanical properties of similar materials.

| Number | Lithology            | Compressive strength (KPa) | Thickness (mm) | Sand | Material quality (kg) |
|--------|----------------------|----------------------------|----------------|------|-----------------------|
| 23     | Sandy mudstone       | 86.53                      | 46             | 28.91| 4.05                  |
| 22     | Medium-grain sandstone| 150.97                     | 84             | 50.25| 6.28                  |
| 21     | Sandy mudstone       | 86.53                      | 45             | 28.13| 3.94                  |
| 20     | Medium-grain sandstone| 150.97                     | 91             | 54.75| 6.84                  |
| 19     | Sandy mudstone       | 86.53                      | 44             | 27.34| 3.83                  |
| 18     | No.2-1 coal seam     | 28.5                       | 91             | 59.88| 5.99                  |
| 17     | Sandy mudstone       | 86.53                      | 63             | 39.06| 5.47                  |
| 16     | Medium-grain sandstone| 150.97                     | 58             | 34.5 | 4.31                  |
| 15     | Sandy mudstone       | 86.53                      | 91             | 57.03| 7.98                  |
| 14     | Medium-grain sandstone| 150.97                     | 38             | 22.5 | 2.81                  |
| 13     | Limestone 2          | 486.3                      | 11             | 6.33 | 0.63                  |
| 12     | Sandy mudstone       | 86.53                      | 19             | 11.72| 1.64                  |
| 11     | Medium-grain sandstone| 150.97                     | 25             | 15   | 1.88                  |
| 10     | Sandy mudstone       | 86.53                      | 25             | 15.63| 2.19                  |
| 9      | Medium-grain sandstone| 150.97                     | 31             | 18.75| 2.34                  |
| 8      | Sandy mudstone       | 86.53                      | 63             | 39.06| 5.47                  |
| 7      | Limestone 1          | 486.3                      | 56             | 31.64| 3.16                  |
| 6      | 3307B protective layer| 86.53                      | 19             | 11.72| 1.64                  |
| 5      | Sandy mudstone       | 86.53                      | 23             | 14.06| 1.97                  |
| 4      | No.1-8 coal seam     | 28.5                       | 8              | 8.2  | 0.82                  |
| 3      | Medium-grain sandstone| 150.97                     | 20             | 12   | 1.5                   |
| 2      | Limestone            | 486.3                      | 25             | 14.06| 1.41                  |
| 1      | Sandy mudstone       | 86.53                      | 21             | 13.28| 1.86                  |

Shock and Vibration
Figure 9: Experimental model device and scheme. (a) Model device; (b) model scheme.

Figure 10: Continued.
Floor fracture of No. 2-1 coal seam
Separation scope: 72.8 m
Separation fracture: 7.3 m

Separation fracture / The channel of gas migration
Separation scope: 84.0 m

Recompaction scope: 115.2 m
Separation layer closure
Coal wall supporting scope

Effective protection scope
Downhill pressure relief angle: 68°
Upward pressure relief angle: 55°
Effective protection scope: 160 m

Figure 10: Fracture characteristics of strata while mining the rock-coal composite protective layer. (a) Working face is advanced to 32.4 m; (b) working face is advanced to 48.5 m; (c) working face is advanced to 72.8 m; (d) working face is advanced to 84.0 m; (e) working face is advanced to 115.2 m; (f) working face is advanced to 160 m.

Figure 11: Vertical stress curve for the No.2-1 coal seam in the mining of the rock-coal composite protective layer.

Figure 12: Vertical displacement curve for the overlying strata in the mining of the rock-coal composite protective layer.
6. Summary and Conclusion

We used the numerical method combined with the similarity simulation experiment to investigate the protective effect of rock-coal composite protective layer mining with gently inclined thick coal seam. The vertical stress, vertical displacement, expansion deformation, and fracture characteristics evolution law of the protected layer with the mining of the rock-coal composite protective layer were obtained. Then, we adopted engineering measurements to verify the effect of the mining rock-coal composite protective layer. The main conclusions can be summarized as below:

1. The numerical simulation analysis shows that while mining the rock-coal composite protective layer, the vertical stress in the No. 2-1 coal seam is lower than the stress in the original strata. After completing the composite protective layer mining, the minimum vertical stress of the No. 2-1 coal seam has been reduced to 3.46 MPa. The maximum vertical displacement of the No. 2-1 coal seam is 455.01 mm. The maximum expansion deformation of the No. 2-1 coal seam is 9.77‰, the effective pressure relief range is as long as 160 m, and the pressure relief effect is remarkable.

2. The similarity simulation experiment revealed that when the rock-coal composite protective layer working face is advanced to 72.8 m, the overburden fracture develops to the No. 2-1 coal seam. The gas...
content and gas pressure of the No. 2-1 coal seam began to release and decrease gradually. After completing protective layer mining, the minimum vertical stress of the No. 2-1 coal seam is 4.0 MPa. The maximum vertical displacement of the No. 2-1 coal seam is 640 mm. The maximum expansion deformation of the No. 2-1 coal seam is 26.37%. The effective protection range reaches 130 m. No. 2-1 coal seam is located at the boundary of the bending zone and the fracture zone. Combined with pressure relief gas drainage, it can reasonably achieve the purpose of gas release.

(3) The variation law of gas drainage parameters in the protected layer corresponds to the vertical stress distribution law of the protected layer in numerical simulation and similarity simulation. With the exploitation of the protective layer, the pressure of the protected layer begins to release. The permeability of the coal seam increases, and the average gas drainage concentration reaches 20%–30%, which is 2-3 times that before the protective layer mining.

**Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest**

The authors declare no conflicts of interest.

**Authors’ Contributions**

J. M. conceived and designed the experiments; J. M. and J. H. performed the experiments; J. M. and J. H. analyzed the data; J. M. and C. H. wrote the paper; J. M. validated the paper.

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