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Research Article

Analysis of Strata Behavior Process Characteristics of Gob-Side Entry Retaining with Roof Cutting and Pressure Releasing Based on Composite Roof Structure

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In order to explore the characteristics of rock pressure distribution with roof cutting and pressure releasing under different composite roof structures and optimize the support design of entry retaining, the mechanical analysis and numerical simulation are used to analyze the structure characteristics of composite roof and the effect of roof cutting under composite roof in this paper. Besides, taking the 8304 working face of Tashan Coal Mine as an example, the results of theoretical research are verified by field-monitoring data of hydraulic supports, working resistance, and roadway deformation. The results show that the weak interlayer in the composite roof is easily damaged under the external force and the distribution of the layer has a key effect on the roof characteristics. When the weak interlayer is located at the middle of the roof cutting layer range, the demand of the roadway support strength is the highest; when the weak interlayer is located at the top of the roof cutting layer range, the demand of the roadway support strength is the lowest. Furthermore, with the increase of the height of the weak interlayer in the roof cutting layer range, the stress concentration peak of the coal wall side decreases first and then rises, then descends again, and the trend can be fitted by the curve of a three-degree equation.

1. Introduction

The increasing tension of coal resources and the deepening of mining depth are the two major trends in coal mining field of China and even the world at this stage [1, 2]. With the continuous development of supporting materials and mining equipment, the coal recovery rate of underground mining has been greatly improved, and the prevention and control of mine pressure has become more and more mature [3]. However, the layout technology of working face with section protective coal pillars is still the mainstream mining mode in China. The setting of section protective coal pillars restricts the further improvement of coal recovery rate in the mining area fundamentally and increases the workload of entry excavation and the risk of rock burst in entry [4]. Therefore, the traditional longwall mining working face layout technology needs to be optimized.

As a nonpillar mining method, gob-side entry retaining (GER) technology can cancel the setting of section coal pillars during the working face mining, and the entry of a working face can be maintained along the gob for the continuous use by adjacent working face. Since the 1950s, the GER technology has been an important technical development direction of coal mining in China [5]. However, the traditional entry retaining is usually realized by roadside support, roadside filling, and other means. The cost of these entry-retaining methods is high and the implementation process is complex. Besides, compared with the working face mining advance, the entry-retaining implementation often lags behind, which seriously restricts

the application and development of the GER technology [6, 7].

In view of this, Professor He et al. further put forward the roof cutting pressure releasing gob-side entry retaining (RCPRGER) technology based on the short-arm beam theory in 2008 [4, 8]. The core of this technology is to carry out directional presplitting blasting along the goaf side of entry roof in the working face mining advance direction under the condition of roof strengthening with high pretightening force constant resistance large deformation anchor cable (CRLDAC). Then, the horizontal stress transfer between the goaf roof and entry roof can be cutoff in the vertical roof cutting range, and after the working face mining advance, the goaf roof will collapse and the gangue can fill the goaf effectively due to the bulking coefficient. This technology realizes the entry retaining automatically without any coal pillars and other filling materials, which solves the two difficult problems effectively of high confining pressure and difficult support of GER. Furthermore, the efficiency of entry retaining increased greatly and the cost reduced greatly, which greatly improved the application scope of GER technology.

In recent years, the RCPRGER technology has been successfully tested in many mines and the researches of key technology and relevant equipment have been relatively mature. For examples, Sun et al. take the 1610 working face of Nantun Coal Mine as an example to elaborate the key parameters design method of RCPRGER technology under thin coal seam [9]; Guo et al. take the 3118 working face of Jiayang Coal Mine as an example, the parameters of roof presplitting and entry supporting technology are studied in depth [10]; and Zhang et al. put forward the CRLDAC + single hydraulic prop combined reinforcement support method in the application of RCPRGER technology in Tangshangou Coal Mine [11]. During the test and popularization of the technology, the composite roof mines account for more than two-thirds of the all test mines, but under different roof composite structures, the characteristics of strata pressure process show great differences. Therefore, in order to summarize the characteristics of strata pressure with roof cutting pressure releasing under composite roof and explore its formation mechanism, this paper studies the problem by means of mechanical analysis and numerical simulation and then taking the practice of RCPRGER under the composite roof in 8304 working face of Tashan Coal Mine as an engineering example to further verify the research conclusions in this paper. The research results can be used as references for further popularization and optimization of RCPRGER technology.

2. Research Background

2.1. Principle of RCPRGER. The core of RCPRGER technology is cutting off the horizontal stress transfer between the goaf roof and entry roof through the entry roof cutting with bidirectional concentrated tension blasting technology along the working face advance direction. Meanwhile, under the reinforcing support of the entry roof with CRLDAC, a stress difference will be formed between both sides roof of roof cutting slit after working face mining. Namely, the roof deformation of retained entry can be controlled after working face mining advance, whereas the goaf roof will collapse along the roof cutting slit in time, and the gangue from goaf roof collapse can support the overlying strata effectively with breaking and bulking (as shown in Figure 1) [4, 12].

2.2. Structure Characteristics of Composite Roof. Composite roof, also known as separation roof, is one of the common roof structures in coal mine. It is usually composed of more than one layer of soft or hard rock strata. The roof characteristics are various under different structural conditions, and the support of composite roof is one of the difficult problems in the field of roadway support at home and abroad [13].

Composite roof usually has three characteristics, such as soft, weak, and thin. The heights of weak interlayers in roof directly affect the overall mechanical properties of roof [14]. According to the structure of composite roof, it can be summarized as three types: (1) upper soft and lower hard type, (2) middle composite type, and (3) upper hard and lower soft type. In the traditional layout of working face with longwall mining, the upper soft and lower hard roof has no obvious pressure appearing and foreboding after the working face mining and before the goaf roof caving, and the roof caving velocity is faster, caving area is larger, and caving strength is more intense, which requires higher support strength of hydraulic supports in working face and advance support in the entry. The roof falling accident is easy to occur under upper hard and lower soft roof condition. Besides, with the normal mining advance of working face, the roof first collapse after working face is easy to occur in the goaf under this roof condition, but the gangue from the first collapse is difficult to fill up the goaf space. Namely, the upper hard strata will be suspended in a large area, and the subsequent weighting of roof will still show a higher peak. The middle composite-type roof has both characteristics of above two roof types, whose firs collapse strength is slightly weaker than that of upper soft and lower hard roof, and the suspension length of upper hard stratum after working face is slightly shorter than that of upper hard and lower soft roof, but the roof weighting is still sudden and periodic.

3. Composite Roof Structure and Roof Cutting Effect

3.1. Stress Analysis of Composite Roof. Because of the obvious laminated structure of composite roof, the roof can be simplified into a rock beam model for analysis. The formula for calculating the periodic fracture step of single layer is as follows [15]:

$$L_{OZ} = \sqrt{\frac{M_Z[\sigma]}{3\gamma}}, \tag{1}$$

where L_{OZ} is the periodic fracture step of the single layer, M_Z is the thickness of single layer, $[\sigma]$ is the tensile strength of the rock layer, and γ is the bulk density of the rock layer.

When analyzing the whole roof composite structure, the typical composite roof with a weak interlayer can be taken as an example, and the unit length along the entry axis can be

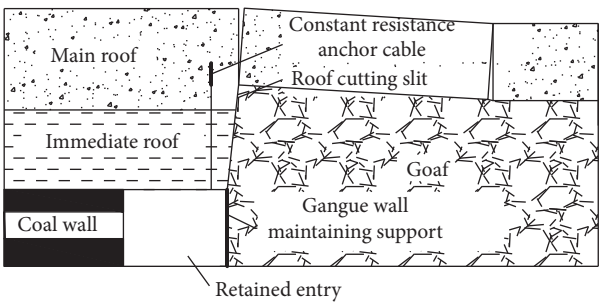

Figure 1: Principle of RCPRGER technology.

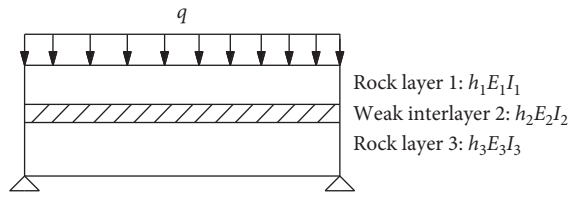

Figure 2: Diagram of composite roof beam model: q is the uniformly distributed load of roof beam model; h_1, h_2, and h_3 are the thicknesses of each rock layer; E_1, E_2, and E_3 are the elasticity moduli of each rock layer; and I_1, I_2, and I_3 are the inertia moments of each rock layer.

taken to establish the rock beam model as shown in Figure 2 [16]. Because the working face is usually long under long wall mining and the analysis emphasis is the working face tendency direction in this study, based on the rock mass mechanical property of poor tensile capacity, the influence from working face strike direction can be neglected and the roof stress analysis can be simplified into 2D plane problem [17, 18]. Considering that the support at both ends of the composite roof beam has a great influence on its stress state, the conversion coefficient m is introduced: when the two ends are fixed (the coal walls are stable), $m = 1$; when the two ends are simply supported (the coal walls are soft and have certain joints), $m = 1/3$; and when the two ends are half-fixed (between the two situations mentioned above), $m = 2/3$. The maximum (minimum) stress in the layered rock beam is

$$\sigma_{\substack{\max\\ \min}} = \frac{\sigma_x \pm Mm}{W} = \frac{\sigma_x \pm 6Mm}{k^2 h}, \tag{2}$$

where M is the maximum bending moment; W is the bending section coefficient of composite beams, $W = h^2k/6$; h is the height of composite roof beam; k is the coefficient related to the delamination of composite roof beam and k is 1.00, 0.75, 0.70, or 0.65 when the delamination number of composite roof beam is 1, 2, 3, or 4; and σ_x is the horizontal tectonic stress.

Based on the rock beam model shown in Figure 2, it can be seen from the mechanics of materials:

$$M = \frac{ql^2}{24}, \tag{3}$$

$$I = \frac{bh}{12}, \tag{4}$$

$$\frac{1}{\rho} = \frac{M}{(EI)} = \frac{12M}{(Eh)}, \tag{5}$$

where l is the span of the composite roof beam, I is the moment of inertia, b is the section width of the composite roof beam with a value of 1 m, ρ is the bending radius, and E is the elastic modulus. In any states before the failure of the composite roof, all the rock layers of the roof are a whole; that is, the deformation curvature of each rock layer is the same:

$$\frac{1}{\rho} = \frac{M_1}{(E_1I_1)} = \frac{M_2}{(E_2I_2)} = \frac{M_3}{(E_3I_3)}. \tag{6}$$

It can be seen that the higher the rigidity is, the greater the bending moment of the rock layer is, and the sum of the bending moment of each roof layer is the bending moment of the whole roof:

$$M_1 + M_2 + M_3 = M. \tag{7}$$

From equations (5)–(7),

$$\begin{cases} M_1 = \dfrac{ME_1h_1}{(E_1h_1 + E_2h_2 + E_3h_3)}, \\ M_2 = \dfrac{ME_2h_2}{(E_1h_1 + E_2h_2 + E_3h_3)}, \\ M_3 = \dfrac{ME_3h_3}{(E_1h_1 + E_2h_2 + E_3h_3)}. \end{cases} \tag{8}$$

In addition, the composite roof is mainly characterized by compressive stress under horizontal tectonic stress. The magnitude of horizontal stress on the roof strata is related to the thickness of the strata. Assuming that the roof is subjected to horizontal stress resultant force of N, the component force of each rock layer is

$$\begin{cases} N_1 = \dfrac{Nh_1}{h}, \\ N_2 = \dfrac{Nh_2}{h}, \\ N_3 = \dfrac{Nh_3}{h}. \end{cases} \tag{9}$$

According to equations (8) and (9), equation (2) can be solved as shown in the following:

$$\begin{cases} \sigma_{\substack{\max\\ \min}} = \dfrac{h_1}{h}N \pm \dfrac{ql^2}{12(E_1h_1 + E_2h_2 + E_3h_3)}\dfrac{E_1}{h_1}, \\ \sigma_{\substack{\max\\ \min}} = \dfrac{h_2}{h}N \pm \dfrac{ql^2}{12(E_1h_1 + E_2h_2 + E_3h_3)}\dfrac{E_2}{h_2}, \\ \sigma_{\substack{\max\\ \min}} = \dfrac{h_3}{h}N \pm \dfrac{ql^2}{12(E_1h_1 + E_2h_2 + E_3h_3)}\dfrac{E_3}{h_3}. \end{cases} \tag{10}$$

This formula shows that the thickness and elasticity modulus of each stratum have greatest influences on its mechanical properties under certain other conditions. Because the weak interlayer in the composite roof is usually of small thickness and low strength, the stress in the weak interlayer is larger than that in other strata during the process of roof deformation, and it is easy to form stress concentration. At the same time, formula (1) shows that the periodic fracture step of a single layer is also small under the condition of small thickness, which also shows that the single layer-bearing capacity of weak interlayer is weak. In a word, under the condition of composite roof, the weak interlayer is more prone to bending and tensile failure because of its smaller strength and greater concentrated stress under external force than other rock strata. After the failure of weak interlayer, other hard rock layers will also show flexural deformation, and subsequent rock pressure mainly depends on the mechanical properties of the hard rock layers.

3.2. Roof Cutting Effect under Composite Roof. Based on the analysis of the failure characteristics of composite roof, the strata pressure behavior of composite roof under the condition of roof cutting pressure releasing can be preliminarily deduced. As shown in Figure 1, in order to make the gangue collapsed from the roof cutting range can fill the goaf adjacent to retained entry effectively, the roof cutting height is usually calculated according to the bulking coefficient of goaf roof (shown as equation (11)). When the roof is composed of more than one layer, the bulking coefficient can be calculated according to the weight of the thickness of each layer (shown as equation (12)) [19]:

$$H_{\mathrm{F}} = \frac{(H_{\mathrm{M}} - \Delta H_1 - \Delta H_2)}{(K-1)}, \tag{11}$$

$$K = \sum_{i=1}^{n} K_i \frac{D_i}{H_{\mathrm{M}}}, \tag{12}$$

where H_F is the roof cutting height; H_M is the mining height; ΔH_1 is the roof subsidence volume; ΔH_2 is the floor heave volume; K is the roof rock's bulking coefficient; n is the number of rock layers in the roof cutting range, $n \geq 1$; D_i is the thickness of each rock layer ($1 \leq i \leq n$); and K_i is the bulking coefficient of each rock layer ($1 \leq i \leq n$).

Taking the typical composite roof with a weak interlayer as an example, the strata pressure behavior characteristics on the inclination section of working face can be analyzed when the weak interlayer is located at upper, middle, and lower of roof cutting range, respectively. The plan of GER with roof cutting is shown in Figure 3(a), and the inclination section of the retained entry with a weak interlayer at different heights is shown in Figure 3(b).

The specific analysis is as follows:

The horizontal connection between the goaf roof and the entry roof is cut off by the roof cutting slit in the inclined direction, so the stress transfer from the goaf roof to the entry roof can only be transmitted indirectly through the strata above the roof cutting range. When the weak interlayer is located at the top of the roof cutting range, the roof collapse in the roof cutting range has little pulling force on the above stratum because of the poor tensile ability of the weak stratum. Meanwhile, the gangue collapsed from the roof can fill up the goaf adjacent retained entry effectively, so the retained entry is the most stable under this condition; that is, the support strength demand of the retained entry is lower. When the weak interlayer is located at the middle of the roof cutting range, the lower stable stratum is easy to collapse and will not cause excessive pulling force to the upper stratum. However, the upper stable stratum in the roof cutting range is difficult to collapse smoothly under its dead weight due to its thin thickness, which may cause larger pulling force to the above stratum. So the support strength demand of the retained entry is higher under this condition. When the weak interlayer is located at the bottom of the roof cutting range, although there is a certain bonding force between upper stable stratum in the cutting range and stratum above the cutting range, the upper stable stratum can also collapse smoothly under its dead weight due to its thick thickness. So, the support strength demand of the retained entry is middle under this condition. If using Q_1, Q_2, and Q_3 to represent the support strength requirements of retained entry under above three roof types, then $Q_2 > Q_3 > Q_1$.

4. Stress Analysis of Composite Roof with Roof Cutting

According to the design principle of roof cutting height in the RCPRGER technology, it is known that the gangue collapsed from the roof cutting range can fill up the goaf adjacent to the retained entry effectively with breaking and bulking after the working mining advance. Therefore, under this technology, the structures of rock layers above the roof cutting range have little influence on the strata pressure behavior around retained entry [20, 21]. In the previous section, three typical cases of weak interlayer located in the upper, middle, and lower of the roof cutting range have been preliminarily analyzed. In order to further study the stress distribution law of composite roof under roof cutting and guide the retained entry support, this section still takes the typical composite roof with a weak interlayer as an example and adopts the numerical simulation method to analyze the stress distribution under different heights of the weak interlayer.

4.1. Numerical Model. This study uses FLAC 3D software for numerical simulation, in order to facilitate the follow-up field practice to validate the simulation conclusion effectively, taking the geological condition of 8304 working face in Tashan Coal Mine as a reference for modeling. The modeling size is 200 m × 170 m × 50 m, including 30 m thick roof and 17 m thick floor. In the numerical calculation model, the working face strike length is 200 m, the working face inclination length is 130 m, the mining height is 3 m, the entry width is 5 m, and the mining footage is 100 m. Besides, the roof cutting height is 8 m and the roof cutting angle is 15°

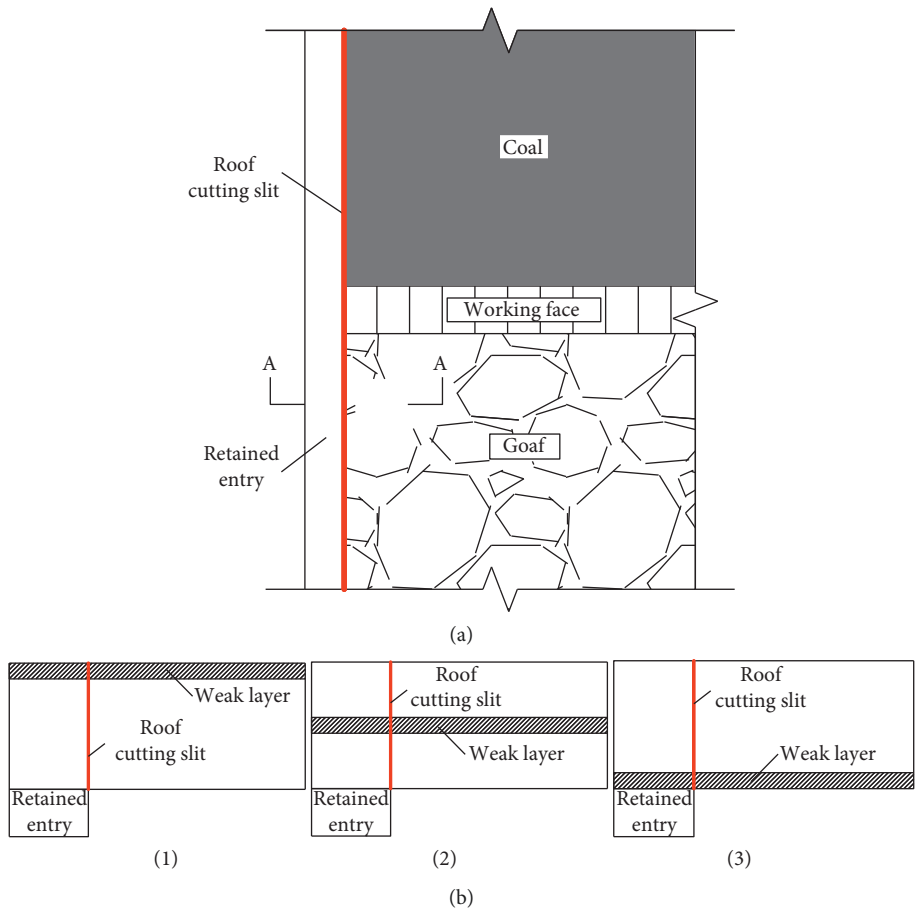

Figure 3: Schematic diagram of roof cutting with different composite roof structures: (a) layout of roof cutting entry retaining and (b) inclination section of retained entry: (1) weak layer in upper, (2) weak layer in middle, and (3) weak layer in lower.

(from vertical direction to goaf). The lithology of the weak interlayer is set as mudstone, whose thickness is 1 m, and the lithology of the stable stratum is set as fine sandstone. The 17 m thick floor is set as fine sandstone (0–9 m), siltstone (9–13 m), and mudstone (13–17 m), according to the field conditions. The 22 m thick roof above the roof cutting range is set as medium sandstone (28–31 m), mudstone (31–33 m), medium sandstone (33–35 m), fine sandstone (35–36 m), and siltstone (36–50 m). The modeling parameters are shown in Table 1, and according to the different heights of the weak interlayer, there are 8 models in this study, namely, the mudstone layer of each model is, respectively, located at 0-1 m, 1-2 m, . . . , and 7-8 m above the working face roof. The typical model is shown in Figure 4 whose weak interlayer is located at 0-1 m above the working face roof.

4.2. Simulation Results. The numerical calculation models with one weak interlayer at different heights are simulated and calculated, and the vertical stress distributions of entry surrounding rocks on the working face inclination section are intercepted as Figure 5. On the whole, when the weak interlayer is located at the lower and upper of the roof cutting range, the stress concentration intensity in the coal wall is lower and the stress concentration scope is smaller, and the goaf side roof is easier to collapse. However, when the weak interlayer is located at the middle of the roof cutting range, the situation is opposite, which is mutually corroborated with the analysis results of the previous section. In order to further analyze the relationship between the stress distribution around retained entry and the height of weak interlayer, and to provide theoretical guidance for the design of retained entry support, the simulation postprocessing software TECPLOT is used to extract the stress concentration peak values from simulation results shown in Figure 5. The peak pressures of surrounding rock under different roof conditions are summarized and fitted, the summarized results are shown in Table 2, and the fitted results are shown in Figure 6.

The numerical simulation results show that the stress concentration peak value of surrounding rock first decreases, then rises, and then decreases with the increase of the height of weak interlayer in the roof cutting range. The change trend can be fitted by the curve of a three-degree equation. The fitting equation is $y = -0.0004x^3 + 0.0039x^2 - 0.0102x + 10.88$ ($R^2 = 0.9508$), and the fitting curve is in good agreement with the simulation value. According to the fitting result, when the weak interlayer is above the roof 2.9–5.9 m, the peak value of stress concentration in the coal wall is higher. On the basis of the analysis of the previous section, when the weak interlayer height rises from the bottom of the roof cutting range

Table 1: Modeling parameters of each rock layer.

Lithology	Bulk density (kN/m^3)	Tensile strength (MPa)	Internal friction angle (°)	Cohesion (MPa)	Bulk modulus (GPa)	Shear modulus (GPa)
Mudstone	23	3.2	28	0.2	0.20	0.15
Fine sandstone	24	7.3	32	1.0	3.81	3.05
Siltstone	23	4.3	32	0.8	2.11	1.86
Medium sandstone	25	8.4	33	2.6	11.49	7.26

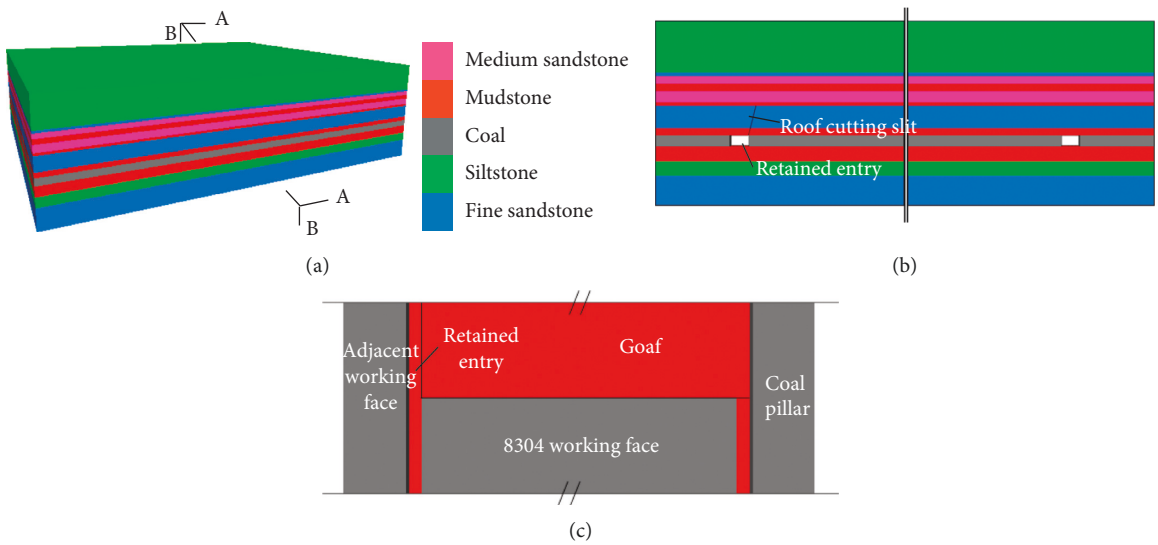

Figure 4: Typical numerical calculation model: (a) 3D model, (b) Section A-A, and (c) Section B-B.

preliminarily, the roof part below the weak interlayer is easier to collapse, and the above stable layer can also collapse smoothly under its dead weight, so the stress concentration strength of the coal wall shows a downward trend; when the weak layer height continues to rise, the difficulty of the above stable layer collapse under its dead weight increases, and the cohesive force with the strata above the roof cutting range also increases, so the stress concentration strength of coal wall presents an upward trend, whereas when the weak interlayer height continues to increase, then most rocks in the roof cutting range can collapse smoothly to realize the effective filling of goaf, and the stress concentration strength of coal wall presents a sharp decline. In conclusion, under this geological condition with roof cutting, when the weak interlayer is located in the middle 2.9–5.9 m of the roof cutting range, the retained entry support should be strengthened. When the roof has more than one weak interlayer, the roof cutting effect of each weak layer should be considered, respectively, and the reinforcement support measures of entry should be designed comprehensively.

5. Engineering Practice

In order to verify the above theoretical analysis and numerical simulation conclusions, taking the practice of RCPRGER under the medium-thick coal seam and compound roof conditions of 8304 working face in Tashan Coal Mine as an engineering example, the field monitoring of stress in working face and retained entry deformation is used to be compared with above conclusions.

5.1. Engineering Geological Conditions. The 8304 working face of Tashan Coal Mine is the first mining face in the east wing of panel 3 in the Datong coalfield, Shanxi Province, China. It is adjacent to the 8305 working face, and the layout plan is shown in Figure 7. The basic parameters of the working face are shown in Table 3. In order to accurately grasp the lithologic change of composite roof in the 8304 working face, six roof lithologic peepholes are arranged in the entry to be retained. After peeping, the lithologic section of roof is drawn as Figure 8.

According to the weighted calculation of the thickness of each stratum on the roof, the bulking coefficient of the roof is taken as 1.41, then the cutting height is designed as 7.5 m based on equation (11), as the division datum line shown in Figure 8. Because there is a mudstone interlayer around 6.5–8 m above the working face roof in the first 200 m area of mining advance (area I), to ensure anchor cable support effect and make the roof collapse easily in the roof cutting range, the roof cutting height is increased to 8 m. In the later 470 m area of mining advance (area II), the roof cutting height is maintained 7.5 m as original design. The final roof cutting height design is shown as the roof cutting height line in Figure 8. Furthermore, in order to reduce the friction effect to retained entry roof when the goaf roof collapsing

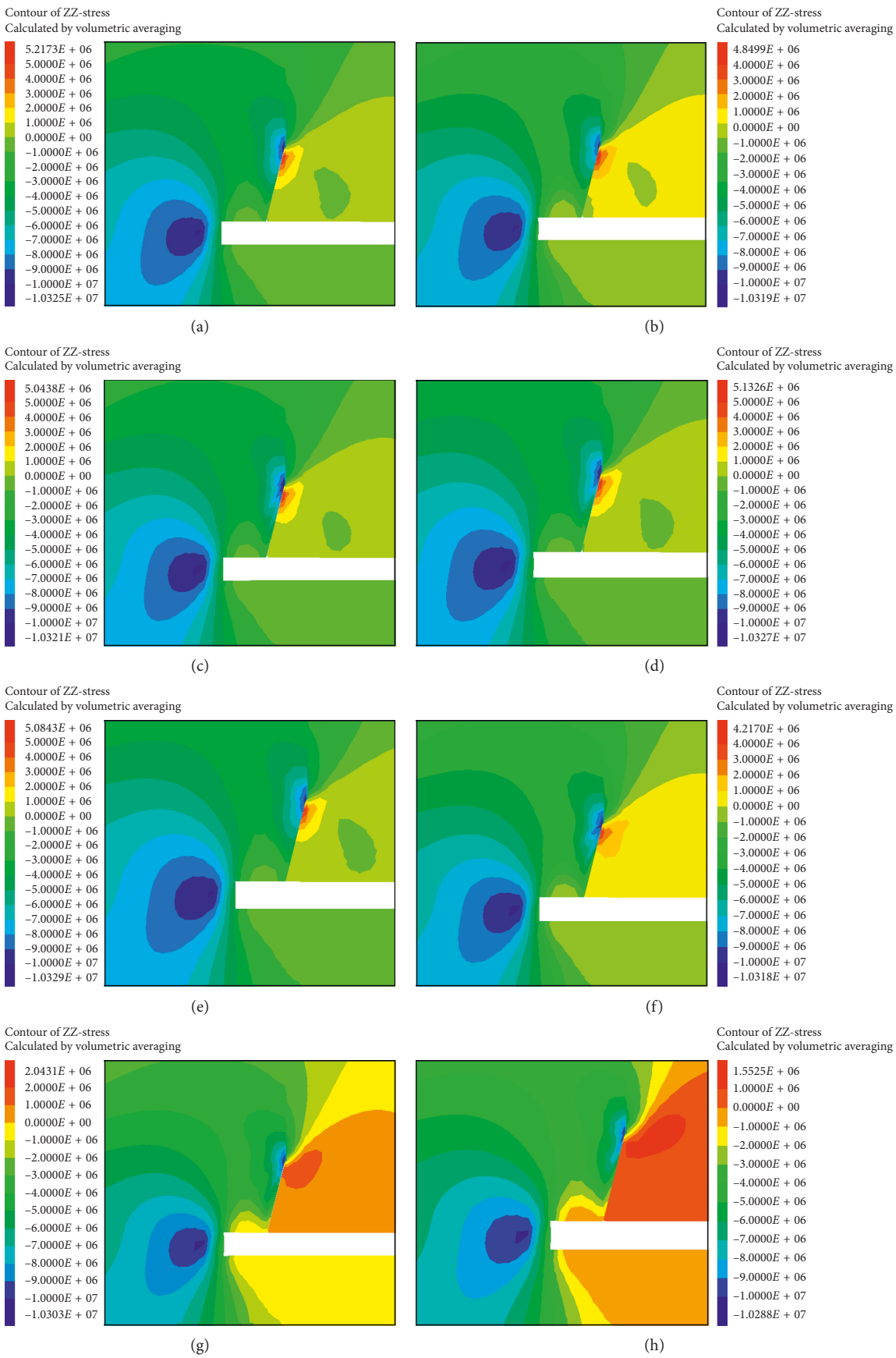

Figure 5: Numerical calculation results: mudstone layer located at (a) 0-1 m above the working face roof, (b) 1-2 m above the working face roof, (c) 2-3 m above the working face roof, (d) 3-4 m above the working face roof, (e) 4-5 m above the working face roof, (f) 5-6 m above the working face roof, (g) 6-7 m above the working face roof, and (h) 7-8 m above the working face roof.

Table 2: Simulation results statistics.

Weak layer location	0–1 m above the working face roof	1-2 m above the working face roof	2-3 m above the working face roof	3-4 m above the working face roof	4-5 m above the working face roof	5-6 m above the working face roof	6-7 m above the working face roof	7-8 m above the working face roof
Stress concentration peak value (MPa)	10.325	10.319	10.321	10.327	10.328	10.318	10.303	10.288

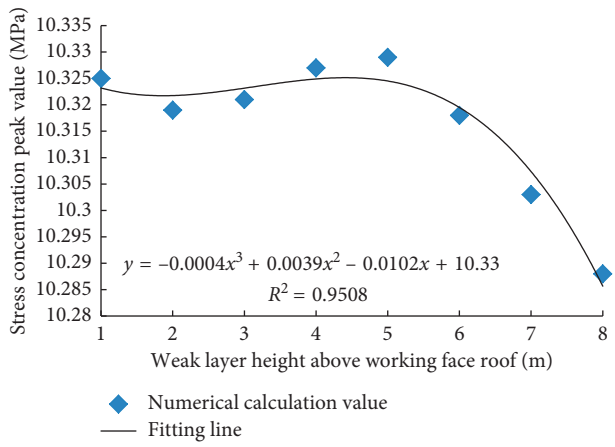

Figure 6: Statistical analysis of peak intensity.

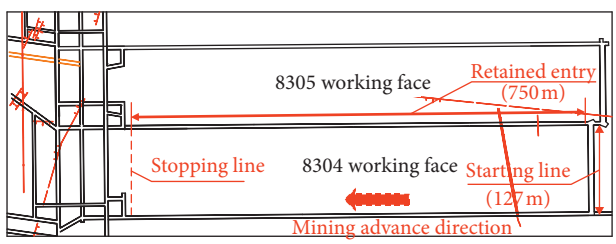

Figure 7: Layout of the 8304 working face.

Table 3: Basic parameters of the 8304 working face.

Coal seam thickness/average thickness (m)	1.80–3.55/3.1	Buried depth (m)	367–411
Mining height (m)	3.1	Coal seam dip angle/average dip angle (°)	2~6/4
Working face strike length (m)	670	Working face inclination length (m)	127
Immediate roof/thickness (m)	Mudstone/1.47	Immediate floor/thickness (m)	Mudstone/3.2
Main roof/thickness (m)	Fine sandstone/3.88	Main floor/thickness (m)	Siltstone/3.1

along the roof cutting slit, the roof cutting angle is design as 15° from the vertical direction to the goaf.

The comprehensive mechanized mining method is adopted in the test face, the maximum daily mining speed is 12.7 m/d, the average daily mining speed is 8.3 m/d, and the mining speed is faster. The entry designed to be retained is the tail lane of the 8304 working face, which is used for ventilation and pedestrian during the working face mining advance. The section of the test entry is rectangular with bolt, mesh, and cable supporting, and the section size is 5.0 m × 3.1 m. According to the mining experience of the adjacent working face, the advance temporary support of entry is designed as Figure 9(a), each support section is arranged with 3 single pillars, and the row spacing is 1.0 m. The lagging temporary support of retained entry is designed as Figure 9(b), each support section is arranged with 5 single pillars, considering that the entry roof on the roof cutting side is prong to subsidence deformation, the row spacing is 0.5 m on the roof cutting side, and the row spacing is still 1.0 m in other four rows.

5.2. Monitoring Results and Analysis of Retained Entry. The 8304 working face is mined and the entry is retained according to above designs, and the field effect of entry retaining is shown in Figure 10. The working resistance of hydraulic supports in working face is monitored during the mining process, and the monitoring result of hydraulic support on the roof cutting side is shown in Figure 11.

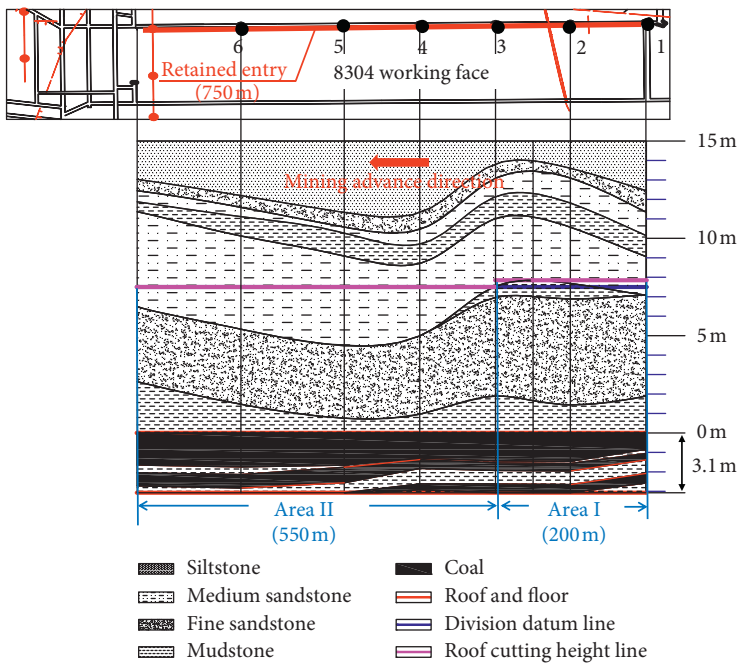

Figure 8: Roof lithology and division of the 8304 working face in Tashan Coal Mine: 1, 2, . . . , 6 are the six roof lithologic peepholes located at footage 0 m, 100 m, 200 m, 300 m, 400 m, and 550 m of the working face, respectively.

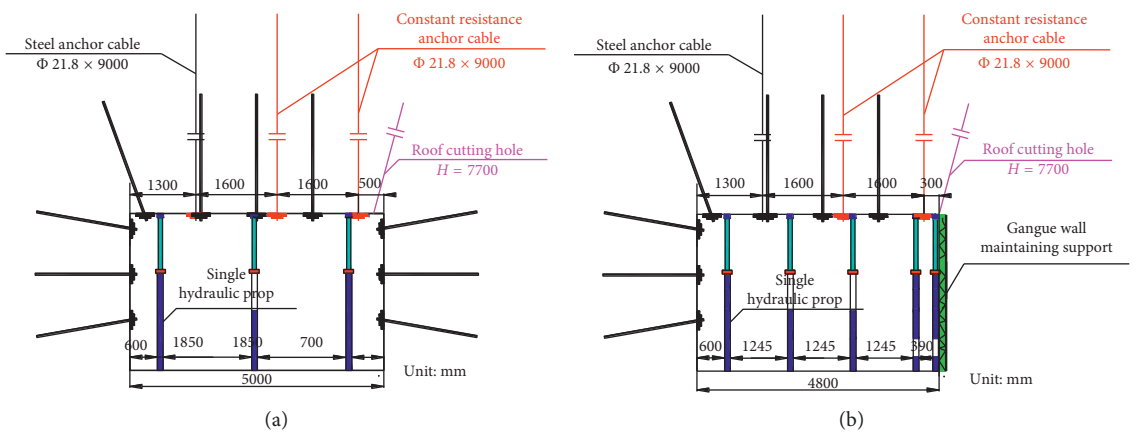

Figure 9: Temporary support design of the 8304 working face: (a) advance temporary support and (b) lagging temporary support.

(a) (b)

Figure 10: Field-retaining effects.

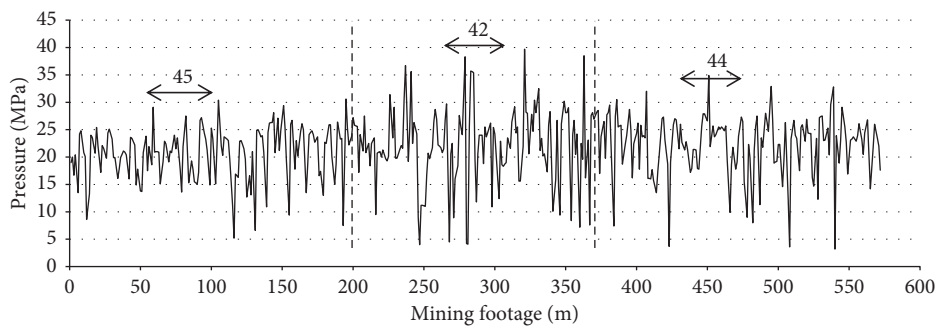

Figure 11: Hydraulic support resistance monitoring results of the 8304 working face on roof cutting side.

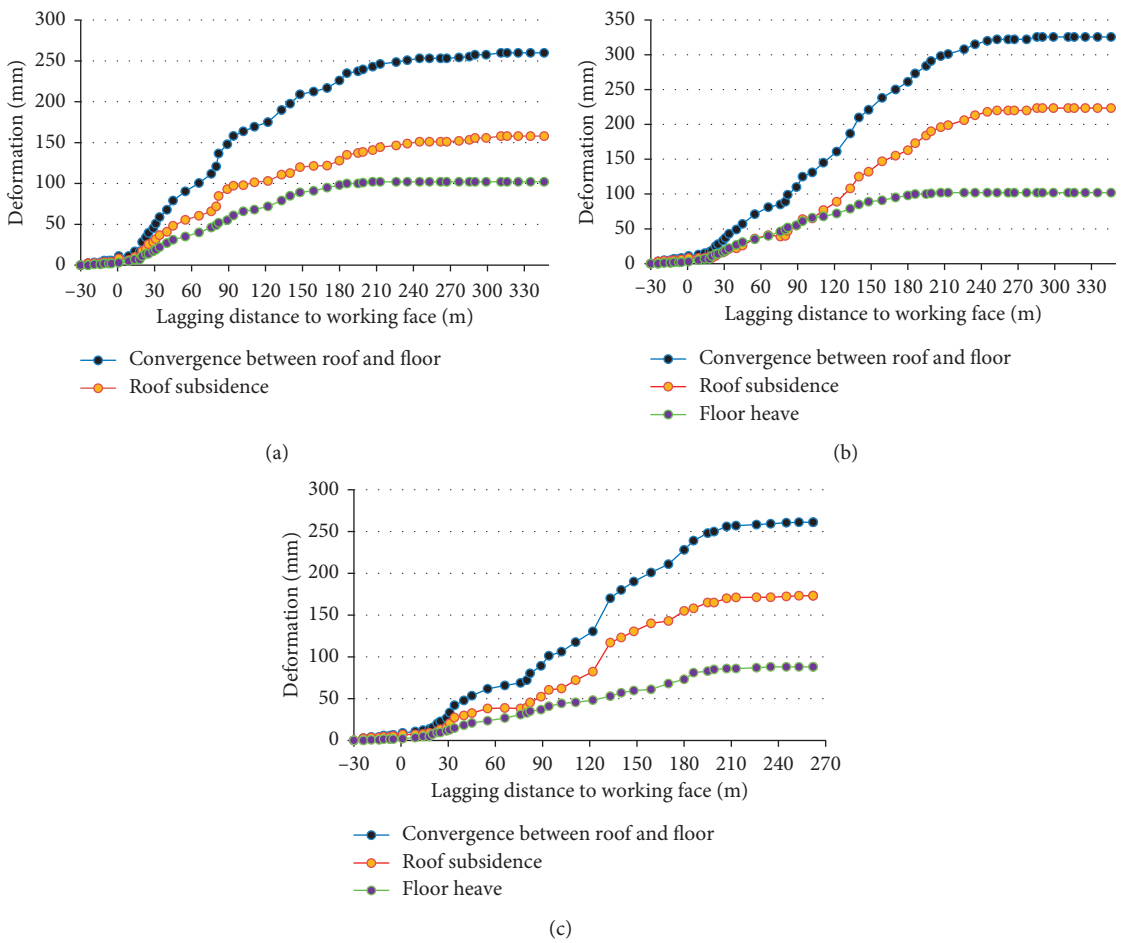

Figure 12: Monitoring results of retained entry deformation by the cross-point method: (a) footage 100 m, (b) footage 300 m, and (c) footage 500 m.

During the mining advance of the working face, the average length of roof suspension after the working face is 7.6 m in the first 200 m area of mining advance, and the average length increases to 18.7 m in the range of 200 m to 375 m of mining advance. In order to reduce the roof suspension length, a group loosening blasting of goaf roof is carried out with 15 m spacing, and then the roof suspension average length is reduced to 13.2 m in the 375–670 m mining advance area. According to the monitoring result in Figure 11, the roof periodic weighting step on the roof cutting side is about 45 m in the first 200 m area, and the maximum weighting strength is 30.4 MPa. The roof periodic weighting step on the roof cutting side is about 42 m in the 200–375 m area and the maximum weighting strength is 39.7 MPa. The roof periodic weighting step on the roof cutting side is about 44 m in the 375–670 m area, and the maximum weighting strength is 34.9 MPa.

At the same time, the deformation of retained entry is also monitored with the cross point method, and the monitoring results of footage 100 m, 300 m, and 500 m are shown in Figure 12. At footage 100 m, the roof to floor convergence is finally stable at 259.9 mm, including

102.0 mm floor heave and 157.9 mm roof subsidence. At footage 300 m, the roof to floor convergence is finally stable at 325.5 mm, including 104.0 mm floor heave and 221.5 mm roof subsidence. At footage 500 m, the roof to floor convergence is finally stable at 262.3 mm, including 89.3 mm floor heave and 173.9 mm roof subsidence.

Comparing with the lithologic section of roof shown in Figure 8, it can be seen that there are two weak layers in the roof cutting range within the first 200 m area, which are located at the lower and upper of roof cutting range, respectively, although there is only one weak layer at the lower of roof cutting range in the area after 200 m and the upper stable layer is medium sandstone. According to the above conclusions in Sections 2 and 3, it can be inferred that the goaf roof in first 200 m area should be easier to collapse and the support pressure of working face and retained entry will be smaller, whereas the length of roof suspension in rear 470 m area will increase, and thus the support pressure of working face and retained entry will increase correspondingly. The field monitoring of mine pressure and retained entry deformation verifies the above conclusions to a certain extent. Meanwhile, in order to reduce the retained entry deformation and improve the entry retaining quality, the reinforcement support measures and goaf roof loosening blasting measures should be designed appropriately under the roof condition like rear 470 m area of the 8304 working face in the further popularization and application of the roof cutting pressure releasing technology. Then, the application effect and scope of this new GER technology will be further improved.

6. Conclusions

(1) Based on the deduction of the laminated structure of composite roof, it is found that under the condition of the composite roof, the bearing capacity of the weak interlayer is poor, and it is easy to produce stress concentration and tensile deformation or failure under the external force. The distribution of the weak interlayer has a key influence on the overall characteristics of the roof.

(2) Taking a typical composite roof with a weak interlayer as an example, the roof cutting pressure releasing effects under the conditions of different weak interlayer heights are deduced and analyzed on inclination section, and the qualitative conclusion is drawn as follows: when the weak interlayer is located at the top of the roof cutting range, the support strength demand of the retained entry is the lowest; when the weak interlayer is located at the middle of the roof cutting range, the support strength demand of the retained entry is the highest; and when the weak interlayer is located at the bottom of the roof cutting range, the support strength demand of the retained entry is middle.

(3) Quantitative study on the relationship between the height of weak seam and the effect of roof cutting pressure releasing is carried out by means of numerical simulation. The result shows that the peak value of stress concentration on the side of coal wall first decreases, then rises, and then decreases with the increase of the height of weak seam in the roof cutting range, and the change trend can be fitted by the curve of a three-degree equation.

(4) Taking the 8304 working face of Tashan Coal Mine as an example, it shows that the goaf roof in the first 200 m area is easier to collapse, and the support pressure of working face and retained entry is also smaller; when the length of roof suspension in rear 470 m area increases, the support pressure increases correspondingly. The field monitoring verifies the above conclusions, and on this basis, the following design ideas of retained entry support are put forward.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Manchao He and Xingen Ma are contributed equally to this work.

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References

[1] H. Kang, D. Niu, Z. Zhang et al., "Deformation characteristics of supporting rock and supporting technology of gob-side entry retaining," *Chinese Journal of Rock Mechanics and Engineering*, vol. 29, no. 10, pp. 1977–1987, 2010.

[2] M. Alber, R. Fritschen, M. Bischoff, and T. Meier, "Rock mechanical investigations of seismic events in a deep longwall coal mine," *International Journal of Rock Mechanics and Mining Sciences*, vol. 46, no. 2, pp. 408–420, 2009.

[3] Y. Xue, "From tradition to modern times: evolution of coal mining technology in China," *Journal of Hubei Polytechnic University (Humanities and Social Science)*, vol. 30, no. 05, pp. 7–15, 2013.

[4] M. He, Z. Song, A. Wang et al., "Theory of longwall mining by using roof cutting shortwall team and 110 method," *Coal Science and Technology Magazine*, vol. 1, no. 1, pp. 1–9, 2017.

[5] J. Shi, N. Ma, and Z. Bai, "Analysis on roof broken location of gateway retained along goaf and technology of roof support," *Coal Science and Technology*, vol. 41, no. 7, pp. 35–38, 2013.

[6] Y. Li and H. Xinzhu, "Mechanical analysis of stability of key blocks of overlying strata for gob-side entry retaining and calculating width of roadside backfill," *Rock and Soil Mechanics*, vol. 33, no. 4, pp. 1134–1140, 2012.

[7] M. Sheshpari, "A review of underground mine backfilling methods with emphasis on cemented paste backfill," *Electronic Journal of Geotechnical Engineering*, vol. 20, pp. 5183–5208, 2015.
[8] M. He, H. Xie, S. Peng et al., "Study on rock mechanics in deep mining engineering," *Chinese Journal of Rock Mechanics and Engineering*, vol. 24, no. 16, pp. 2803–2813, 2005.
[9] X. Sun, X. Liu, G. Liang et al., "Key Parameters of gob-side entry retaining formed by roof cut and pressure releasing in thin coal seams," *Chinese Journal of Rock Mechanics and Engineering*, vol. 33, no. 7, pp. 1449–1456, 2014.
[10] Z. Guo, J. Wang, T. Cao et al., "Research on key parameters of gob-side entry retaining automatically formed by roof cutting and pressure release in thin coal seam mining," *Journal of China University of Mining and Technology*, vol. 45, no. 9, pp. 879–885, 2016.
[11] G. Zhang, Y. Xu, and P. Ge, "Research on cut gob-side entry retaining in thin coal seam of Tangshan ditch," *Chinese Journal of Rock Mechanics and Engineering*, vol. 5, no. 47, pp. 468–477, 2018.
[12] X. Ma, M. He, J. Wang et al., "Study on design of chamber supporting behind cutting hole under condition of gob-side entry retaining in 8304 face of Yanya coal mine," *Coal Technology*, vol. 36, no. 12, pp. 30–33, 2017.
[13] D. Wu and F. Shen, "Quantitative criteria of interlayer separation stability of complex roof in tunnels," *Chinese Journal of Rock Mechanics and Engineering*, vol. 33, no. 10, pp. 2040–2046, 2014.
[14] F. Yang, L. Wang, A. He et al., "Failure mechanism and bolting support technique of complex roof," *Journal of Mining and Safety Engineering*, vol. 25, no. 3, pp. 286–289, 2008.
[15] H. Li, D. Jiang, and D. Li, "Analysis of ground pressure and roof movement in fully-mechanized top coal caving with large mining height in ultra-thick seam," *Journal of China Coal Society*, vol. 39, no. 10, pp. 1956–1960, 2014.
[16] S. Gu, F. Su, and X. Cui, "Analysis on deformation and failure law of complex roof in seam gateway," *Coal Science and Technology*, vol. 40, no. 5, pp. 20–24, 2012.
[17] X. Ma, M. He, J. Wang, Y. Gao, D. Zhu, and Y. Liu, "Mine strata pressure characteristics and mechanisms in gob-side entry retention by roof cutting under medium-thick coal seam and compound roof conditions," *Energies*, vol. 11, no. 10, p. 2539, 2018.
[18] A. M. Suchowerska, R. S. Merifield, and J. P. Carter, "Vertical stress changes in multi-seam mining under supercritical longwall panels," *International Journal of Rock Mechanics and Mining Sciences*, vol. 61, pp. 306–320, 2013.
[19] Y. Gao, M. He, J. Yang et al., "Experimental study of caving and distribution laws of gangues influenced by roof fracturing in pillarless mining with gob-side entry retaining," *Journal of China University of Mining and Technology*, vol. 47, no. 1, pp. 116–127, 2018.
[20] Z. Ma, Z. Guo, X. Liu et al., "Study on breaking rules and mechanics characteristics of gangue falling off in roof cutting and entry retaining," *Coal Engineering*, vol. 49, no. 11, pp. 94–98, 2017.
[21] X. Ma, M. He, Y. Wang et al., "Study and application of roof cutting pressure releasing technology in retracement channel roof of Halagou 12201 working face," *Mathematical Problems in Engineering*, vol. 2018, Article ID 6568983, 15 pages, 2018.