Research Article

Deformation Mechanism and Control of the Surrounding Rock during Gob-Side Entry Driving along Deeply Fully Mechanized Caving Island Working Face

Fei Liu ¹ and Yongsheng Han ²

¹School of Resources and Civil Engineering, Suzhou University, Suzhou, Anhui 234000, China

²Department of Water Resources Engineering, Shandong Water Conservancy Vocational College, Rizhao, Shandong 276826, China

Correspondence should be addressed to Yongsheng Han; yongshenghan998@126.com

Received 24 February 2021; Accepted 30 July 2021; Published 19 August 2021

Academic Editor: Jia Liu

Copyright © 2021 Fei Liu and Yongsheng Han. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The deformation control of the surrounding rock during gob-side entry driving along deeply fully mechanized caving island working face is one of the main bottlenecks affecting the successful and efficient production in modern mining. The prior ordinary fully mechanized caving theories have been difficult in ensuring the safe and efficient mining along island working face during gob-side entry driving under the complex conditions in the west. Therefore, it is of great theoretical and practical significance to carry out the research on the deformation mechanism and control of the surrounding rock during gob-side entry driving along deeply fully mechanized caving island working face. This paper, by means of experimental research, theoretical analysis, numerical calculation, and field industrial test, systemically researched the deformation characteristics of the surrounding rock and the law of strata behaviors during gob-side entry driving along deeply fully mechanized caving island working face.

1. Introduction

Fully mechanized caving mining is an advanced coal mining method. Since it came out in the late 1950s, after decades of testing and application, it has been rapidly developed in nearly ten coal-producing countries [1] in the world. From the late 1970s to the early 1980s, fully mechanized caving mining became one of the main methods of mining high seams in France, Hungary, and the former Yugoslavia [2]. Fully mechanized caving mining technology [3–5], with its characteristics of low cost, low input, high yield, high efficiency, high benefit, safety and reliability, and simple system as well as its technical storage advantages has gradually replaced the slice longwall method and has become the main technical method to achieve high yield and high efficiency in mining high seams in China.

During fully mechanized caving mining, the backstop-ping roadway of the working face generally is developed along the coal seam floor. The roadway is a full coal road

[6] whose roof and two sides are all coal. Setting coal pillars [7–10] has always been the traditional roadway protection method in coal mines. The traditional method of setting coal pillars is to set a coal pillar with a certain width between the transportation roadway in the upper section and the ventilation roadway in the lower section, so that the roadway in the lower section can avoid the fixed peak area of abutment pressure. The drifting and application of double transportation roadways in sections is simple in technical management, which is beneficial to ventilation, transportation, drainage, and safety [11]. However, the coal pillar loss is as high as 10%–30%; in addition, influenced by secondary mining [12, 13] of the ventilation roadway, it is difficult to maintain the roadway and the supporting cost is high. The propagation of abutment pressure from the coal pillar to the floor not only affects the mining of the adjacent coal seam and the stability of the floor roadway but also becomes a hidden trouble that causes strong strata behaviors. In order to improve the recovery rate of coals during fully mechanized caving mining,

domestic scholars put forward a method, namely, setting narrow coal pillars in the backstopping roadway at the gob side during gob-side entry driving [14–19], and the coal pillar width is generally between 4 and 7 m. Due to the increase of mining depth year by year, it is more and more difficult to maintain the roadway at the gob side during fully mechanized caving mining, which restricts the developing speed of a fully mechanized caving face and seriously affects the construction of a high-yield and efficient working face.

The coal pillar width is closely related to the strata behaviors [20] of the coal pillar, backstopping roadway support, maintenance cost, safe mining at the working face, and coal resource recovery rate. At present, some coal mines in China still rely on experience to determine the coal pillar width [21, 22], which lacks scientificity and pertinence. How to give consideration to resource recovery rate and the prevention of large deformation of the coal pillar and how to reasonably determine the coal pillar width has become a research topic for many scholars. Influenced by geological conditions, mining successions, and other factors [23], some mines adopt island working face mining in the mining process. However, compared with the nonisland working face, the law of overlying strata activity of the stope is very intense, the stress concentration degree is high [24, 25], and the strata behavior pressure is high. Therefore, it is of great theoretical significance and practical application value to carry out the research on the deformation mechanism and control of the surrounding rock during gob-side entry driving along the deeply fully mechanized caving island working face. Statistics of the roof fall accidents from year 2001 to 2013 is shown in Table 1.

2. Engineering Geological Conditions

The experimental mine is located in Shaanxi province (Figure 1). The coal seam in the working face of the test area is stable, and the thickness of the coal seam is 7.2–8.46 m, with an average thickness of 7.83 m. The coal seam is nearly horizontal, and the dip angle is between 2° and 4°, with an average of about 3° coal seam with gangue 1–5 layers, thickness 0.20 m–2.10 m, average 1.15 m, and coal seam structure of 0.80 (0.20), 0.50 (0.30), 0.80 (0.70), 1.90 (0.30), and 5.60. Through the actual exposure of three main roadways and two roadways in the working face of 42 panels, the geological structure of the working face is simple, and no large structure is found. It is expected that there is no large geological structure in the process of mining. The roof lithology of the coal seam is mainly gray medium-grained feldspar quartz sandstone, followed by gray-black, dark gray siltstone, and fine sandstone interbeds. The floor is mainly gray miscellaneous carbonaceous mudstone, with a small amount of gray-white argillaceous sandstone. Detailed lithological descriptions of the rock strata are illustrated in Figure 2.

It can be seen from the experimental results (Figure 3 and Table 2) that the local surrounding rock components of roadway mainly include illite/montmorillonite mixed layer, quartz, calcite, kaolinite, siderite, and dolomite. Kaolin, illite, and montmorillonite are clay argillaceous expansive rocks with strong hydrophilicity and swelling in water. The fracture

TABLE 1: Statistics of the roof fall accidents from year 2001 to 2013.

Year	Number of roof fall events	Deaths
2001	267	380
2002	771	913
2003	1036	1239
2004	787	988
2005	749	913
2006	103	218
2007	36	144
2008	19	85
2009	14	43
2010	16	57
2011	15	64
2012	13	58
2013	9	21
Total	3835	5123

FIGURE 1: Location of the experimental mine, Shaanxi, China.

joints in the local surrounding rock of the roadway in the northern wing strata are developed, and the roadway is seriously flooded. Water is easy to enter the surrounding rock. The kaolinite and illite are softened, broken, and disintegrated when encountering water, while the montmorillonite expands when encountering water and then softens and loosens.

3. Theoretical Calculation of Narrow Coal Pillar Width along Goaf Roadway

Reasonable selection of the narrow coal pillar width in the roadway along the goaf is one of the key links in roadway excavation and support technology. A large or small coal pillar size is not conducive to roadway surrounding rock support and maintenance. According to the roadway protection mechanism of the narrow coal pillar along the goaf, the coal pillar is as small as possible under the premise of considering the improvement of the anchor force and support effect.

FIGURE 2: Stratigraphic column and geological description.

FIGURE 3: X-ray diffraction pattern.

According to the limit equilibrium theory [26] of coal pillar stability,

$$B = X_1 + X_2 + X_3, \quad (1)$$

where X_1 is the width of plastic zone generated in the coal body at the goaf side after the mining of the upper working face, and its value is calculated according to the following formula:

$$X_1 = \frac{mA}{2tg\varphi_0} \ln \left| \frac{k\gamma H + C_0/tg\varphi_0}{C_0/tg\varphi_0 + P_z/A} \right|, \quad (2)$$

where B is the coal pillar width; m is the height of roadway, 4.6 m; A is the coefficient of the horizontal pressure, 0.85; φ_0

is the internal friction angle of the coal seam interface, 30° ; C_0 is the cohesive force of the coal seam interface, 5 MPa; k is the stress concentration factor, 3; γ is the average bulk density of overlying strata, 25 kN/m^3 ; H is the depth of the roadway, average 491 m, 500 m in the calculation; P_z is the support resistance of the anchor bolt to the coal side, 0.08 MPa; X_2 is the effective length of the anchor, 2.5 m; X_3 is the enrichment of the coal pillar width considering the large thickness of the coal seam and is generally calculated by 15~35% of the $X_1 + X_2$ value.

Substituting the mechanical parameters of the roadway surrounding rock and the assumed supporting parameters into the above formula, the theoretical value of the width of the narrow coal pillar along the goaf can be obtained, and the final calculated coal pillar width is 13.9-15.7 m. The

TABLE 2: Experimental results of X-ray diffraction.

Sample number	#1	#2	#3	#4	#5
Main components	I/S, Q, C	I/S, Q, K, S	Q, K, D, S	I/S, Q, D, K	Q, S, K

FIGURE 4: Calculation model of theoretical coal pillar width.

FIGURE 5: Solving process of FLAC^{3D}.

calculation model of theoretical coal pillar width is shown in Figure 4.

4. Finite Element Method Simulation

4.1. 3-D Fast Lagrangian Method. The 3-D fast Lagrangian method is a numerical analysis method based on the 3-D explicit finite difference method, which can simulate the 3-D mechanical behavior of rock and soil or other materials. 3-D fast Lagrangian analysis adopted the explicit finite difference scheme to solve the governing differential equation of the field and applied a mixed-unit discrete model to accurately simulate the yield, plastic flow, softening, and large deformation of materials. It had its unique advantages especially in the elastic-plastic analysis and large deformation analysis of materials, construction process stimulation, and other fields. The solving process of FLAC^{3D} is shown in Figure 5.

4.2. Establishment of Mechanical Calculation Model. The coal pillar width between the 4204 working face and the 4208 working face was 246~248 m. After roadway driving, the stress of the roof and the floor was redistributed, and the surrounding rock was deformed, moved, and even damaged.

FIGURE 6: Initial model.

However, the range of the influence on the surrounding rock after roadway driving was definite, and the stress change could be ignored at a distance away from the roadway. Therefore, the sizes of the model of the 4206 island working face, the transportation roadway, and the ventilation roadway were designed as follows: length $\times$ width $\times$ height = 800 $\times$ 300 $\times$ 40 m, as shown in Figure 6.

Displacement boundary conditions of the model: rolling support was adopted in the X direction to limit the displacement in the X direction; rolling support was adopted in the Y direction to limit the displacement in the Y direction; displacement boundary was adopted at the bottom boundary of the model to limit the displacement in the Z direction; and the free boundary was adopted at the upper boundary of the model to apply vertical stress. The specific boundary conditions of the numerical model are shown in Figure 7.

4.3. Numerical Simulation Scheme Calculation. The displacement of the roof and floor of the transportation roadway and the stress state of the surrounding rock mass in the 4206 island working face in different support parameters were studied. According to the theoretical calculation results, the following three supporting schemes were selected for optimization. The simulation scheme is shown in Table 3.

5. Numerical Result Analysis

5.1. Stress Distribution Characteristics of the Surrounding Rock along the Island Working Face. From the perspective of safety, the narrow coal pillar was set in the stress-relaxed area or the original rock stress area as much as possible during gob-side entry driving. Therefore, the coal pillar width left in the two roadways along the 4206 working face should be larger than the range of the stress-relaxed area.

When backstopping the 4204 working face and the 4208 working face, with the development of the working face, the first weighting of the main roof formed an “O-X” fracture; the periodic weighting formed an arc triangle block at the

FIGURE 7: Boundary setting of numerical calculation model for gob-side entry driving in fully mechanized top coal caving face.

TABLE 3: Supporting scheme.

	Bolt	Anchor cable	Spacing between bolts	Spacing between anchor cables	Preload (moment)	Material
Scheme I	Roof: $\Phi 20 \times 2500$ Side: $\Phi 20 \times 2500$	Roof: $\Phi 21.8 \times 9600$ Side: $\Phi 21.8 \times 6500$	Roof: 800×800 Side: 800×800	Roof: 1600×800 Side: row spacing 800	Bolt: 300 N·m Anchor cable: 210 kN	Bolt: screw thread steel anchor cable: steel strand
Scheme II	Roof: $\Phi 20 \times 2500$ Side: $\Phi 20 \times 2500$	Roof: $\Phi 21.8 \times 9600$ Side: $\Phi 21.8 \times 6500$	Roof: 800×700 Side: 800×700	Roof: 1600×700 Side: row spacing 700	Bolt: 300 N·m Anchor cable: 210 kN	Bolt: screw thread steel anchor cable: steel strand
Scheme III	Roof: $\Phi 20 \times 2500$ Side: $\Phi 20 \times 2500$	Roof: $\Phi 21.8 \times 9600$ Side: $\Phi 21.8 \times 6500$	Roof: 700×700 Side: 700×700	Roof: 1600×700 Side: row spacing 700	Bolt: 300 N·m Anchor cable: 210 kN	Bolt: screw thread steel anchor cable: steel strand

end of the working face, which formed lateral abutment pressure along the 4206 island working face and directly influenced the stability of the set coal pillars during gob-side entry driving. The distribution of the lateral abutment pressure is shown in Figure 8.

A monitoring point was set up every 1 m from the edge of the gob, to monitor the vertical stress in the coal seam and determine the range of the stress-relaxed area and the stress-increased area. The monitoring data are shown in Table 4.

As can be seen from Figure 9, near the edge of the gob, due to the gob near the working face, the coal changed from the 3-D stress state to the 2-D stress state, and the stress inside the coal could be released to the gob. The closer it was to the gob, the more obviously the stress was released, so that the stress-relaxed area was formed at the edge of the gob; at the same time, the roof was broken at the edge of the gob, forming an arc triangular block. This structure caused pressure on the coal and formed stress concentration in front of the stress-relaxed area. That was the stress-increased area. For safety's sake and to reduce the deformation of the coal pillar, the stress-increased area was avoided when setting the coal pillar. As the position advanced forward into the coal, the influence of the stress release at the edge of gob and the bearing pressure of the arc triangle block

on the original rock stress inside the coal became less. When the distance advanced forward enough, the surrounding rock stress returned to be the original rock stress. That was original rock stress area.

It can be seen from the curve that the stress-relaxed area was located 0 to 3 m from the edge of the gob and that the stress-increased area was located 3 to 25 m from the edge of the gob. The minimum vertical stress appeared at 1 m away from the gob, and the vertical stress concentration coefficient was 0.47. The maximum vertical stress appeared at 7 m away from the gob, and the vertical stress coefficient was 2.49; between 3 and 7 m, the vertical stress gradually rose at a faster rate, so it was not suitable to set the coal pillar. When it was 15 m, the vertical stress was 16.9 MPa and the vertical stress coefficient was 1.24, which was 124% of the original rock stress. The minimum vertical stress appeared at 25 m, and the vertical stress concentration coefficient was 1.

5.2. Optimization of Coal Pillar Size at the Island Working Face. In the theoretical calculation, the reasonable range of the width between two coal pillars in the roadway was 13.9~15.7 m, and the width of 12 to 16 m between two coal pillars was considered in the numerical calculation model. Theoretically, after the overlying strata of the gob at 4204 and 4208 working faces became stabilized, the distribution

FIGURE 8: Lateral abutment pressure distribution of 4206 island working face.

TABLE 4: Monitoring table of vertical stress.

Monitoring point	Vertical stress (MPa)	Vertical stress concentration factor	Monitoring point	Vertical stress (MPa)	Vertical stress concentration factor
1	6.4	0.47	14	18.2	1.34
2	9.0	0.66	15	16.9	1.24
3	12.6	0.93	16	16.3	1.20
4	19.8	1.46	17	15.9	1.17
5	28.5	2.10	18	15.5	1.14
6	33.3	2.45	19	15.5	1.14
7	33.9	2.49	20	14.7	1.08
8	29.8	2.19	21	14.6	1.07
9	26.1	1.92	22	14.3	1.05
10	23.5	1.73	23	14.3	1.05
11	21.4	1.57	24	14.0	1.03
12	19.9	1.46	25	13.6	1.00
13	18.7	1.38			

of the surrounding rock stress and the coal pillar stress in the two roadways at the 4206 working face was the same. However, considering that the cross-section size of the transportation roadway was larger than that of the ventilation roadway (the curved cross-section of the transportation roadway was 5800 (width) $\times$ 4600 mm (medium height); the arc cross-section of the ventilation roadway was 5200 (width) $\times$ 3700 mm (medium height)), the surrounding rock stability of the transportation roadway and its influence on the coal pillar were greater than that of the ventilation roadway. Therefore, taking the coal pillar width in the transportation roadway as an example, the simulation research was carried out to select a reasonable coal pillar width. According to the simulation results, the vertical stress inside the coal pillar at 40 m behind the working face was largest, and the plastic zone was most completely developed. Considering that there was no air leakage among the 4206, 4204, and 4208 gob, the coal pillar

in the gob shall not be permeated by cracks and still had a certain bearing capacity. When the coal pillar in the gob could ensure no air leakage and had a certain bearing capacity, the coal pillar during the driving period and the coal pillar in front of the working face during the backstopping period could also ensure no air leakage and have a bearing capacity. Therefore, taking the state of the coal pillar at the working face during the driving and backstopping period and that of the coal pillar 40 m from the back of the gob as the basis for comparison, we, respectively, compared the distribution of stress, deformation, and plastic zone of the coal pillars when the width was 12, 13, 14, 15, and 16 m, to determine the reasonable range of the coal pillar width.

5.2.1. During the Driving Period of the Roadway. The coal pillar stress and roadway deformation state during the driving period of the roadway are shown in Figure 10.

FIGURE 9: Lateral abutment pressure distribution curve of 4206 island working face.

It can be seen from the curve trend that as the coal pillar width increased between 12 and 15 m, the maximum vertical stress inside the coal pillar decreased. When the coal pillar width was small, the coal pillar was influenced by the abutment pressure of the roof, the bearing area was small, and the stress value was relatively large. As the coal pillar width increased continuously between 15 and 16 m, the maximum vertical stress inside the coal pillar continued to decrease, but the decreasing speed was slow. Therefore, it is not recommended to set the coal pillar at 16 m.

Although the maximum vertical stress inside the 15 m coal pillar was not the minimum, it differed from the 16 m coal pillar by less than 1%, which could be regarded as the same. At the same time, compared with the 16 m coal pillar, the width of the 15 m coal pillar was more reasonable and could save coal resources. Therefore, the 15 m coal pillar is preferred.

5.2.2. The Working Face during the Backstopping Period. The coal pillar stress and roadway deformation state at the working face during the backstopping period are shown in Figure 11.

When the coal pillar width was 12 m, the roadway deformation was largest. When the coal pillar width was 16 m, the deformation of the roadway was least, the surface displacement of the coal pillar side was 821 mm, the displacement of entity coal side was 441 mm, and the subsidence of the roof was 750 mm, so the deformation of the roadway was small. When the coal pillar width was 15 m, the curve tended to be stable. With the increase of the coal pillar width, the deformation of the surrounding rock continued to decrease but the change was not obvious.

When the coal pillar width was 12 m to 15 m, the deformation of the coal pillar in the roadway was reduced from 1513 to 845 mm, which was reduced by 44%; when the coal pillar width was 15 m to 16 m, the deformation of the coal pil-

lar in the roadway decreased from 1513 to 821 mm, which was reduced by 46%. Compared with the 15 m wide coal pillar, the change was not obvious. Therefore, the 15 m coal pillar is preferred.

5.2.3. 40 m behind the Gob. The vertical stress, vertical stress concentration coefficient, and roadway deformation of the 40 m coal pillar behind the working face are shown in Figure 12.

When the coal pillar width was 12 to 15 m, the vertical stress inside the coal pillar in the roadway was reduced by 16% from 58.9 to 49.4 MPa; when the coal pillar width was 12 to 16 m, the vertical stress in the coal pillar in the roadway was reduced by 17% from 58.9 to 48.8 MPa. Compared with the 15 m coal pillar, the change was not obvious. Therefore, the 15 m coal pillar is preferred.

When the coal pillar width was 12 to 15 m, the deformation of the coal pillar was reduced by 27% from 3208 to 2327 mm; when the coal pillar width was 12 to 16 m, the deformation of the coal pillar was reduced by 30% from 3208 to 2258 mm. Compared with the 15 m coal pillar, the change was not obvious. Therefore, the 15 m coal pillar is preferred.

The distribution status of the stress, deformation, and plastic zone inside the coal pillar when the coal pillar width was 12, 13, 14, 15, and 16 m was analyzed, respectively, by numerical simulation calculation based on the state of the coal pillar during the roadway driving, of that at 40 m behind the gob, and of that at the working face. The results showed that when the coal pillar width was 15 m, the stress value inside the coal pillar was basically reduced to the lowest, and there was a 4 m elastic zone inside the coal pillar, which had better fire prevention and gas prevention ability; when the coal pillar width was between 12 m and 15 m, the maximum vertical stress inside the coal pillar was reduced with the increase of the coal pillar width; when the coal pillar width was 15 m, the roadway deformation tends to be stable, and the deformation of the surrounding rock continued to decrease with the increase of the coal pillar width, but the change was not obvious. Through the above analysis, it is determined that the recommended width of the coal pillar set in the two roadways of the 4206 island working face is 15 m.

5.3. Research on the Supporting Effect of the Island Working Face

5.3.1. Simulation Analysis of the Transportation Roadway during the Driving Period. As can be seen from Table 5, there was a big difference in the stress and deformation of the surrounding rock by different supporting schemes. In Scheme 1, the stress of the roadway side was relatively concentrated, the subsidence of the roof was large, the floor heave was obvious, and the deformation of the two sides was serious, indicating that the roadway support is insufficient in Scheme 1. Compared with Scheme 1, the stress of the surrounding rock was significantly reduced, and the deformation of the surrounding rock could be reduced by up to 81.7% in Scheme 2 and Scheme 3, indicating that Scheme 2 and Scheme 3

FIGURE 10: Variation trend of surrounding rock stability with coal pillar width during roadway excavation.

FIGURE 11: Variation trend of surrounding rock stability with coal pillar width during working face mining.

can maintain the stable state of the surrounding rock of the roadway, improve the stress distribution, and reduce deformation. Therefore, Scheme 2 or Scheme 3 should be selected as a reasonable supporting scheme.

It can be found from the table that both Scheme 2 and Scheme 3 had achieved a good effect on roadway support and significantly improved the deformation of the surrounding rock, while the supporting effects in Scheme 2 and Scheme 3 were not much different. Considering the economic benefits, Scheme 2 is preferred.

5.3.2. Simulation Analysis of the Transportation Roadway during the Backstopping Period at the 4206 Working Face. As can be seen from Table 6, there was a big difference in

the stress and deformation of the surrounding rock in different supporting schemes. In Scheme 1, the stress of the roadway side was relatively concentrated, the subsidence of the roof was large, the floor heave was obvious, and the deformation of the two sides was serious, indicating that the roadway support is insufficient in Scheme 1. Compared with Scheme 1, the stress of the surrounding rock was significantly reduced, and the deformation of the surrounding rock could be reduced by up to 41.1% in Scheme 2 and Scheme 3, indicating that Scheme 2 and Scheme 3 can maintain the stable state of the surrounding rock of the roadway, improve the stress distribution, and reduce deformation. Therefore, Scheme 2 or Scheme 3 should be selected as a reasonable supporting scheme.

FIGURE 12: The stability of coal pillar 40 m behind goaf changes with the width of coal pillar.

TABLE 5: Comparison of simulation schemes for 4206 transport CIS trough.

Scheme name	Scheme I	Scheme II		Scheme III	
		Increment of decrease	Decrease percentage	Increment of decrease	Decrease percentage
Vertical stress (MPa)	25.8	4.4	17.1%	5.4	20.9%
Roof subsidence (mm)	310.8	244.2	78.6%	247.7	76.7%
Floor heave (mm)	88.1	39.5	44.8%	38.5	43.7%
Deformation of two sides (mm)	330	257.7	78.1%	269.7	81.7%

TABLE 6: Comparison of simulation schemes for 4206 transport CIS trough.

Scheme name	Scheme I	Scheme II		Scheme III	
		Increment of decrease	Decrease percentage	Increment of decrease	Decrease percentage
Vertical stress (MPa)	35.1	3	9%	3.1	9%
Roof subsidence (mm)	714	211	29.5%	238	33.3%
Floor heave (mm)	163	55	33.7%	67	41.1%
Deformation of coal pillar side (mm)	934	221	23.7%	267	28.6%
Deformation of stope side (mm)	430	141	32.8%	149	34.7%

It can be found from the table that both Scheme 2 and Scheme 3 had achieved a good effect on roadway support and significantly improved the deformation of the surrounding rock, while the supporting effects in Scheme 2 and Scheme 3 were not much different. Considering the economic benefits, Scheme 2 is preferred.

6. Practice of 4206 Transportation Roadway Support

6.1. Support Parameters of 4206 Transportation Roadway. Roof and side anchors are, respectively, $\Phi 20 \times 2500$ mm left-handed and right-handed nonlongitudinal reinforcement screw steel anchors, with spacing of 800×700 mm,

and preload of 300 N·m. The roof anchor cable adopts $\Phi 21.8 \times 9600$ mm steel strand, spacing of 1600×700 mm, and preload of 210 kN. The side anchor cable adopts $\Phi 21.8 \times 6500$ mm steel strand, the row spacing is 700 mm, and the preload is 210 kN. The anchor mesh is laid flat, and the steel mesh and the mesh are pressed against each other for 100 mm, and each 100 mm is connected with iron wire. The specific support parameters are shown in Figure 13.

6.2. Observation Data Processing and Analysis. The 4206 island working face adopts gob-side entry driving with a coal pillar of 15 m and adopts the above strengthening support scheme. In the mining process of the 4206 isolated island working face, the cross point method is used to monitor the

FIGURE 13: Schematic diagram of support scheme for 4206 transport roadway.

deformation of the surrounding rock of the roadway. Under the mining influence of the 4206 isolated working face, the roof and floor convergence and the two-side convergence of the roadway are stable within 100 mm, and the coal pillar of roadway protection has not been significantly damaged. The deformation of the roadway is effectively controlled, which ensures the safety and stability of gob-side entry driving.

7. Conclusion

- (i) The X-ray diffraction of the complete coal and rock samples in the test mine was studied. It was found that there were more illite and montmorillonite mixed layers in the #1, #2, and #4 samples, and kaolinite components were found in the #2, #3, #4, and #5 samples. The kaolinite and illite soften, break, and collapse when encountering water, while the montmorillonite expands when encountering water and then softens and loosens, resulting in serious deformation and failure of the roadway
- (ii) According to the limit equilibrium theory of coal pillar stability, it is theoretically determined that the narrow coal pillar width of gob-side entry driving is between 13.9 and 15.7 m
- (iii) The surrounding rock deformation mechanism of gob-side entry driving in the isolated island working face is analyzed, and the stress, deformation, and plastic zone distribution in the coal pillar are simulated and analyzed when the width of the coal pillar is 12, 13, 14, 15, and 16 m. Between 12 m and 15 m, with the increase of the coal pillar width, the maximum vertical stress in the coal pillar decreases. When the coal pillar width is 15 m, the deformation of the roadway tends to be stable. With the increase of the coal pillar width, the deformation of the surrounding rock continues to decrease, but the change is not obvious. Based on comprehensive consideration, it is determined that the recommended width of the coal pillar in two gateways of the 4206 island working face is 15 m
- (iv) The support parameters of three different schemes are verified by numerical simulation, and the final support design scheme is determined. The field practice effect is good

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.

Acknowledgments

This work is supported by the Jiangsu Youth Fund Project (No. BK20200634), the Excellent Young Talents Support

Program in Colleges and Universities (No. gxyq2021221), and the Research Platform Open Project of Anhui Coal Mine Exploration Engineering Technology Research Center of Suzhou University (Nos. 2019ykf01 and 2016ykf02). We sincerely acknowledge the former researchers for their excellent works, which greatly assisted our academic study.

References

- [1] Y.-H. Li, *Comparison study on the ground pressure characteristics of large height and top-caving mining face*, Henan Polytechnic University, 2012.
- [2] J.-W. Li, *Study on surrounding rock control technology for gob-side entry retaining in top-coal caving mining face of Wuyang coal mine*, Liaoning Technical University, 2015.
- [3] L. Yu, S.-H. Yan, H.-Y. Yu, and Z. Zhang, "Studying of dynamic bear characteristics and adaptability of support in top coal caving with great mining height," *Procedia Engineering*, vol. 26, pp. 640–646, 2011.
- [4] W. T. Liu, "Key mining technology for super-long fully mechanized top-coal caving face in soft thick seam," *Coal Engineering*, vol. 15, no. 12, pp. 34–43, 2019.
- [5] C.-H. Fang, *Study of the equipments matching es technology of the top-coal caving fully-mechanized face*, Shandong University of science and technology, 2009.
- [6] L.-S. Zhou, *Study in failure and deformation character of entry along goaf and the technology of strata control about the fully mechanized sublevel caving in deep mine*, Shandong University of science and technology, 2006.
- [7] W. Shi and X.-Z. Xu, "Research on reasonable size of protective coal pillars in coal section," *Meitan Jishu/ Coal Technology*, vol. 29, no. 12, pp. 67–69, 2010.
- [8] Y. Yang and R.-D. Tian, "Numerical simulation research on deformation of coal pillars under gangue filling condition," *Journal of Liaoning Technical University (Natural Science Edition)*, vol. 35, no. 12, pp. 1390–1396, 2016.
- [9] Q. Li, X.-B. Mao, W.-K. Bu, and Z.-G. Ma, "Mechanism of using waste-filling in roadway to control the deformation of covered rock strata," *Journal of China University of Mining & Technology*, vol. 6, no. 37, pp. 745–750, 2008.
- [10] J.-T. Zhang, D.-F. Zhang, W.-Y. Wang, X.-Q. Zhang, and X. Wang, "Reasonable width study of coal pillar preserving gateway in deep mining," *Coal Technology*, vol. 33, no. 8, pp. 76–78, 2014.
- [11] J.-L. Xi, *Study on large section roadway gob-side entry retaining technology in Tunlan*, China University of Mining & Technology (Beijing), 2013.
- [12] R.-J. Si, F.-P. Li, L.-L. Zhao, L.-J. Xu, and H.-X. Feng, "Research on hydraulic fracturing roof cutting and roadway protection technology with wide sublevel coal pillar," *Coal Science and Technology*, vol. 48, no. 7, pp. 282–287, 2020.
- [13] Z.-X. Li and C. Wang, "Section design of mining roadway in "three soft" coal seam based on complex function method," *Safety in Coal Mines*, vol. 46, no. 4, pp. 203–205, 2015.
- [14] Q.-H. Ma and Y.-T. Wang, "Mechanism of narrow pillar protecting roadway and support technology of gob-side entry in deep mine," *Journal of Mining and Safety Engineering*, vol. 26, no. 4, pp. 520–523, 2009.
- [15] P. Gong, Z. Ma, R. R. Zhang, X. Ni, F. Liu, and Z. Huang, "Surrounding rock deformation mechanism and control technology for gob-side entry retaining with fully mechanized

- gangue backfilling mining: a case study,” *Shock and Vibration*, vol. 2017, Article ID 6085941, 15 pages, 2017.
- [16] X.-H. Li, N. Zhang, and C.-J. Hou, “Rational position determination of roadway driving along next goaf for fully-mechanized top-coal caving mining,” *Journal of China University of Mining & Technology*, vol. 29, no. 2, pp. 186–189, 2000.
 - [17] X.-Z. Hua, S. Liu, and Z.-H. Liu, “Research on strata pressure characteristic of gob-side entry driving in island mining face and its engineering application,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 30, no. 8, pp. 1646–1651, 2011.
 - [18] J.-B. Bai, *Surrounding Rock Control of Gob Side Entry Driving*, China University of Mining and Technology press, Jiangsu Xuzhou, 2006.
 - [19] K.-X. Zhang, Y.-J. Zhang, and Z.-Q. Ma, “Determination of the narrow pillar width of gob-side entry driving,” *Journal of Mining & Safety Engineering*, vol. 32, no. 3, pp. 446–452, 2015.
 - [20] E.-B. Yi, D.-L. Xu, J. Sun, M.-L. Xie, and W.-X. Li, “Analysis on prevention and treatment of rock burst with different width coal pillars in isolated island working face,” *Safety in Coal Mines*, vol. 42, no. 11, pp. 126–128, 2011.
 - [21] J.-M. Xi, J.-H. Mao, G.-S. Yang, and J.-F. Wang, “Numerical simulation study on rational coal pillar width in the roadway along goaf,” *Coal Geology & Exploration*, vol. 36, no. 4, pp. 42–45, 2008.
 - [22] J.-D. Liu, *Study on reasonable width of sections coal pillar in mining the ultra-close multiple seam*, Xi’an University of Science and Technology, 2014.
 - [23] Z. Zhou, *Research on surrounding rock control technologies of narrow pillar of mining roadways in island coal face in thick coal seam*, Taiyuan University of Technology, 2014.
 - [24] B.-X. Huang, C.-Y. Liu, B.-S. Zheng, and Q.-Y. Chen, “Research on strata pressure characteristic of gob-side entry driving in island mining face and its engineering application,” *Chinese Journal of Geotechnical Engineering*, vol. 29, no. 6, pp. 932–937, 2007.
 - [25] Y.-M. Cao, X.-Z. Hua, K. Yang, and L.-G. Qi, “Research on the laws of strata behavior in the gob-side entry of the island mining face,” *Safety in Coal Mines*, vol. 44, no. 1, pp. 43–46, 2013.
 - [26] B. Yao, T.-H. Kang, and B. Yin, “Width optimization of narrow coal pillar of gob-side entry driving in isolated fully mechanized caving face,” *Safety in Coal Mines*, vol. 49, no. 6, pp. 130–134, 2018.