Hindawi
Geofluids
Volume 2022, Article ID 1007222, 17 pages
https://doi.org/10.1155/2022/1007222

Research Article

The Coal Pillar Width Effect of Principal Stress Deflection and Plastic Zone Form of Surrounding Rock Roadway in Deep Excavation

Ji Li,[1,2] Rongguang Zhang ,[1] and Xubo Qiang[1]

[1]*School of Energy, Xi'an University of Science and Technology, Xi'an 710054, China*
[2]*Key Laboratory of Western Mine and Hazard Prevention, Ministry of Education, Xi'an 710054, China*

Correspondence should be addressed to Rongguang Zhang; 20203226058@stu.xust.edu.cn

Received 9 September 2021; Accepted 24 February 2022; Published 18 March 2022

Academic Editor: Yong-Zheng Wu

In order to explore the influence of coal pillar width on the principal stress deflection and plastic zone form of surrounding rock in deep roadway excavation, taking 11030 working face transportation roadway of Zhaogu No. 2 Coal Mine as engineering background, theoretical analysis, numerical simulation, and field detection were used to study the effect of coal pillar width on principal stress deflection and plastic zone form and field detection and verification of plastic zone form of surrounding rock in 11030 transportation roadway. The results show that the maximum principal stress is deflected in the vertical direction, which in roadway surrounding rock excavation. The coal pillar width effect of principal stress deflection on both sides of roadway roof and floor and inside coal pillar are more obvious than that of middle roof and floor, coal pillar edge and coal wall position. The deflection of the principal stress affects the morphological distribution of the plastic zone of the surrounding rock, which led to the width effect of coal pillar in roof, and two sides plastic zone are more obvious than that in floor. The principal stress deflection of roadway surrounding rock is highly consistent with the maximum damage depth of plastic zone, and at the same time, the drilling peep results of surrounding rock are basically consistent with the form characteristics of plastic zone in numerical simulation. On this basis, the surrounding rock reinforcement support scheme of 11030 working face transportation roadway was proposed.

1. Introduction

With the increase of coal seam mining depth and mining intensity in China, and the comprehensive influence of production geological conditions and other factors, the deformation and damage of surrounding rock in deep roadways with different width of roadway protection coal pillars show different distribution characteristics. Under the influence of mining and coal pillar width, the stress field direction of roadway surrounding rock will deflect, resulting in the change of form distribution of surrounding rock plastic zone, and then affect the stability of roadway surrounding rock [1–3]. Therefore, the influence of roadway pillar width on principal stress deflection and plastic zone form of surrounding rock in deep roadway excavation is studied, which has important guiding significance for the stability control of surrounding rock in deep roadway.

By using the methods of theoretical analysis and numerical simulation, documents [4, 5] gave the calculation formula of failure width of supporting coal pillar under different failure criteria, revealed the stress distribution characteristics of working face and provided a new idea for retaining coal pillar width and roadway layout. Literature [6] studies showed that the larger the width of the reserved coal pillar, the smaller the proportion of plastic zone form, vertical stress, and horizontal deformation in the coal pillar, and the higher the stability of the coal pillar itself, which was helpful to maintain the stability of roadway surrounding rock. Literature [7] studied the variation law of vertical stress in the surrounding rock and coal pillar width along the open cut tunnel and combined with the limit equilibrium theory of coal body, and the optimized design of coal pillar width along the open cut tunnel was carried out. Literatures [8–10] studied an integrated detection system, established an ultrasonic model, and coupled it with a mechanical model, and the results of the research can predict whether the excavation damage zone, stress distribution, stress rotation, and ultrasonic velocity evolution of the roadway are consistent with the actual situation in the field. Literatures [11–13] proposed the characteristic radii of the plastic zone in the horizontal axis, longitudinal axis, and medial axis according to the damage boundary characteristics of the plastic zone of the roadway, through theoretical calculations and other research methods, in order to reflect the shape characteristics of the plastic zone, evaluate the potential hazard location of the roadway enclosure and the critical point of the roadway dynamic hazard evaluation based on the characteristic radii. The literatures [14, 15], based on mining rock mechanics, focused on the failure behavior and deformation mechanism of rocks with large burial depths and initially established the surrounding rock stress gradient failure theory and research results to provide the theoretical basis and technical support for the future development of deep mineral resources. The above results studied the influence law of coal pillar width on its own stability, roadway deformation, and the size of surrounding rock stress field and displacement field, respectively. However, the related research results on the deflection of the main stress and the form of the plastic zone in the surrounding rock of deep roadway excavation under different widths of coal pillars of the protection roadway are less. Therefore, this paper used numerical simulation to study the characteristics of main stress deflection and plastic zone form distribution of deep roadway excavation surrounding rocks under different widths of coal pillar protecting the roadway and discovered the coal pillar width effect of main stress deflection and plastic zone form and conducted theoretical analysis on the influence of coal pillar width effect on the stability of roadway surrounding rocks. On this basis, the detection and verification of the damage zone of the surrounding rock was carried out in the transporting roadway of 11030 working face of Zhaogu No. 2 Coal Mine, and the corresponding countermeasures for the control of the surrounding rock were proposed.

2. Deformation Characteristics of the Surrounding Rock in Deep Roadway Excavation under Different Coal Pillar Widths

2.1. Deformation Characteristics' Analysis of the Surrounding Rock. In order to study the deformation characteristics of the surrounding rock, which is in deep roadway under different widths of coal pillars of roadway protection, five roadways under different widths of coal pillars of roadway protection were selected through field research, and the deformation characteristics of the roadway surrounding rock after excavation were analyzed, as shown in Table 1.

Through the above case analysis, it can be seen that under different widths of coal pillar, the deformation of the roadway surrounding rock shows differential distribution characteristics, but the width of coal pillar and the amount of surrounding rock deformation does not show a direct correlation, that is, the larger the width of coal pillar, the smaller the amount of deformation of the roadway surrounding rock. And the deformation of the surrounding rock at different locations of the same roadway section shows nonuniform distribution characteristics. For example, in case 5, the maximum deformation of the roadway is 600 mm when 70 m coal pillar is left (two gang convergence), in case 1, the maximum deformation of the roadway is 45 mm when 5 m coal pillar is left (roof subsidence), and in case 2, the deformation of the roadway is different at different locations of the same section when 8 m coal pillar is left (maximum subsidence of roof is 428 mm, and maximum two gang convergence is 270 mm). The essence of the above phenomenon is that the width of the coal pillar will affect the distribution of the plastic zone of the surrounding rock in the roadway.

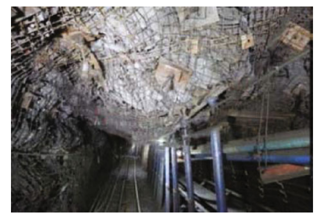
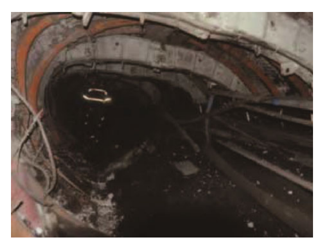
2.2. Factors Influencing the Deformation of the Surrounding Rock. The width of the coal pillar protecting the roadway is an important factor, which influencing the deformation and damage of the roadway excavation. The width of the coal pillar not only affects the size of the surrounding rock stress field but also deflects the direction of the surrounding rock stress field, which changes the form of the plastic zone of the surrounding rock (as shown in Figure 1) [16–19]. Under different pillar widths, the surrounding rock of mining roadway excavation presents differential deformation characteristics. The essence is that the surrounding rock forms different plastic zone. Therefore, this paper will focus on the deflection characteristics of the principal stress of the surrounding rock and the morphological distribution characteristics of the plastic zone under the condition of retaining different roadway pillar widths.

3. Effect of Coal Pillar Width on Deflection of Principal Stress and Plastic Zone Form of Surrounding Rock in Deep Roadway Excavation

3.1. Establishment of Numerical Model. According to the production geological conditions of transportation roadway in 11030 working face of Zhaogu No. 2 coal mine, FLAC^{3D} numerical simulation software was used to build a model with a length of 250 m, a width of 50 m, and a height of 42 m, with a model grid cell size of 0.5 m, as shown in Figure 2.

Displacement constraints were applied to the top and bottom of the model in the vertical direction, and displacement constraints in the horizontal direction were applied around the model, and the initial ground stresses were applied to the model based on the rock formation loads at a burial depth of 700 m, rock laboratory test, and the

Table 1: Deformation characteristics of surrounding rock in roadway excavation.

Roadway	General information	Scene photos	Deformation features
Wulihou coal mine lower group coal tape transport roadway	Average depth of coal seam 550 m; straight wall semi-circular arch roadway: 4.74 m and 4.3 m (net width and net height), wall height 2 m, arch height 2.3 m; 5 m coal pillar.		Maximum shifting in of the top and bottom plates is about 45 mm; the maximum shifting in of the two gangs is about 38 mm.
Transportation roadway of 11030 working face in Zhaogu No. 2 coal mine	Average depth of coal seam 700 m; rectangular roadway: 4.8 m and 3.3 m (width and height); 8 m coal pillar.		Maximum sinking of the roof is about 428 mm; maximum displacement of two sides is about 270 mm.
7608 return air roadway of Wuyang coal mine of Lu'an group	Average depth of coal seam 750 m; rectangular roadway: 5.4 m and 3.2 m (width and height); 15 m coal pillar.		Maximum sinking of the roof is about 200 mm; maximum displacement of two sides is about 700 mm.
Air return roadway in No. 9 mining area of Chensilou coal mine	Average depth of coal seam 900 m; straight wall semi-circular arch roadway: 4.2 m and 4.6 m (net width and net height), wall height 2.4 m, arch height 2.2 m; 13 m coal pillar.		Maximum shifting in of the top and bottom plates is about 200 mm; the maximum shifting in of the two gangs is about 100 mm.
Transportation roadway in No. 7 mining area of Zhaolou coal mine	Average depth of coal seam 910 m; flat-topped domed roadway: 5 m and 4.5 m (net width and net height), upper arc height 2 m, flat top 3 m; 70 m coal pillar.		Maximum sinking of the roof is about 579 mm; maximum displacement of two sides is about 600 mm.

measured ground stresses in the adjacent mine area: 15.30 MPa for vertical stresses, 29.36 MPa (along the x-axis direction), and 16.82 MPa (along the y-axis direction) for horizontal stresses. The model is used Mohr-Coulomb, and the physical and mechanical parameters of each rock layer are shown in Table 2.

The plastic zone distribution characteristics of the roadway surrounding rock were simulated when the width of coal pillar was 4 m, 6 m, 8 m, 10 m, 12 m, 14 m, 16 m, 18 m, and 20 m, respectively, and the main stress direction measurement lines were arranged around the excavated roadway to study the main stress deflection characteristics. The length of each measurement line is 40 m, arranged along the tendency of coal seam, and the interval of measurement line is 0.5 m, and 31 measurement lines are arranged in total, as shown in Figure 3.

3.2. Coal Pillar Width Effect of Principal Stress Deflection of Roadway Surrounding Rock. According to the stress field imposed by numerical simulation, it is known that the maximum principal stress is 29.36 MPa, along the horizontal direction; the minimum principal stress is 15.30 MPa, along the vertical direction, and the following studies are analyzed by the angle between the maximum principal stress and the horizontal direction. Figure 4 shows the contour cloud of the maximum principal stress and the angle between the horizontal directions in the stress field of the roadway enclosure under different coal column widths. From the figure, it can

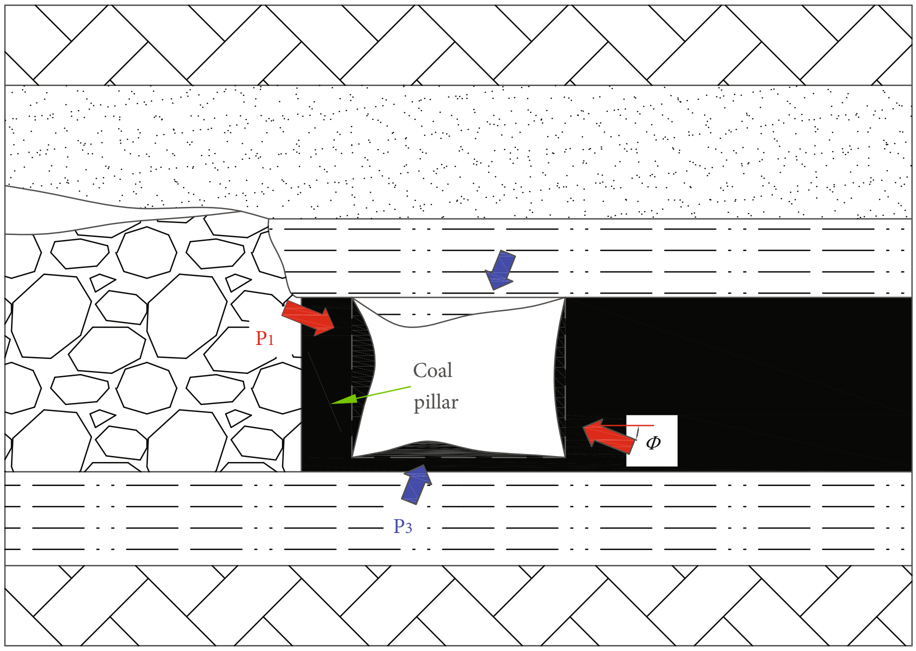


Figure 1: Deformation and failure mechanism of surrounding rock in roadway excavation.

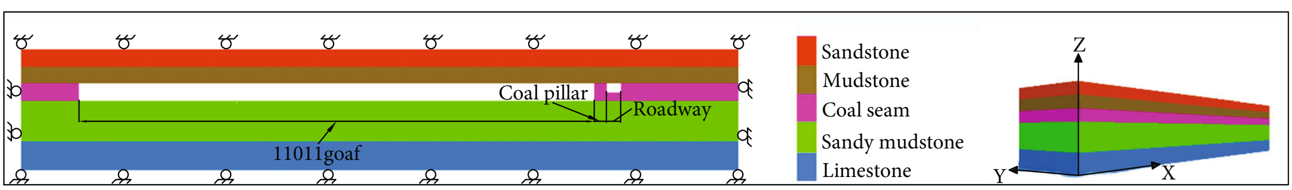


Figure 2: Numerical calculation model.

Table 2: Rock physical and mechanical parameters table.

Rock formation	Internal friction angle (°)	Cohesion (MPa)	Density (kg/m^3)	Shear modulus (GPa)	Bulk modulus (GPa)	Uniaxial tensile strength (MPa)
Sandstone	25	2.8	1500	4.8	5.4	1.5
Mudstone	30	5.24	2200	5.04	8.82	1.48
Coal seam	34	5.36	2500	4.54	10.44	2.6
Sandy mudstone	38	16	2700	9.0	10.2	7.5
Limestone	35	7.9	2300	5.3	8.9	8.71

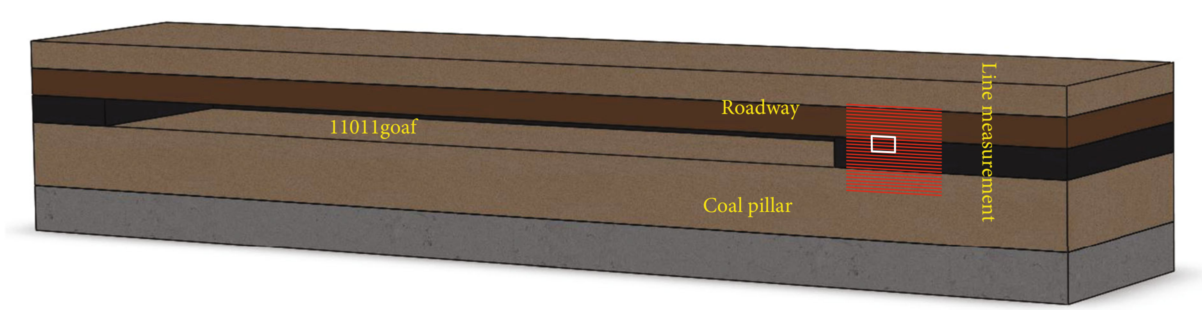
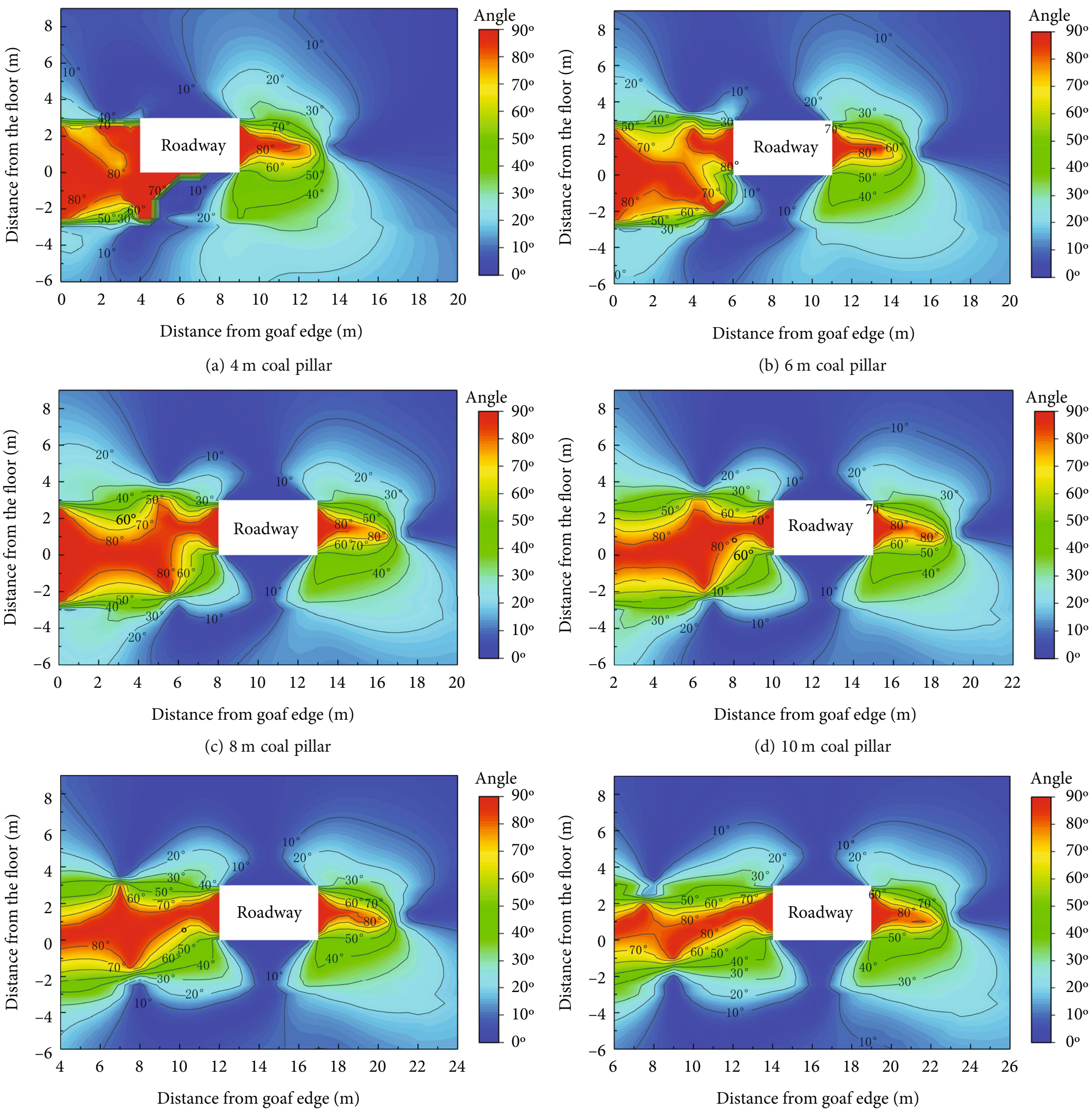
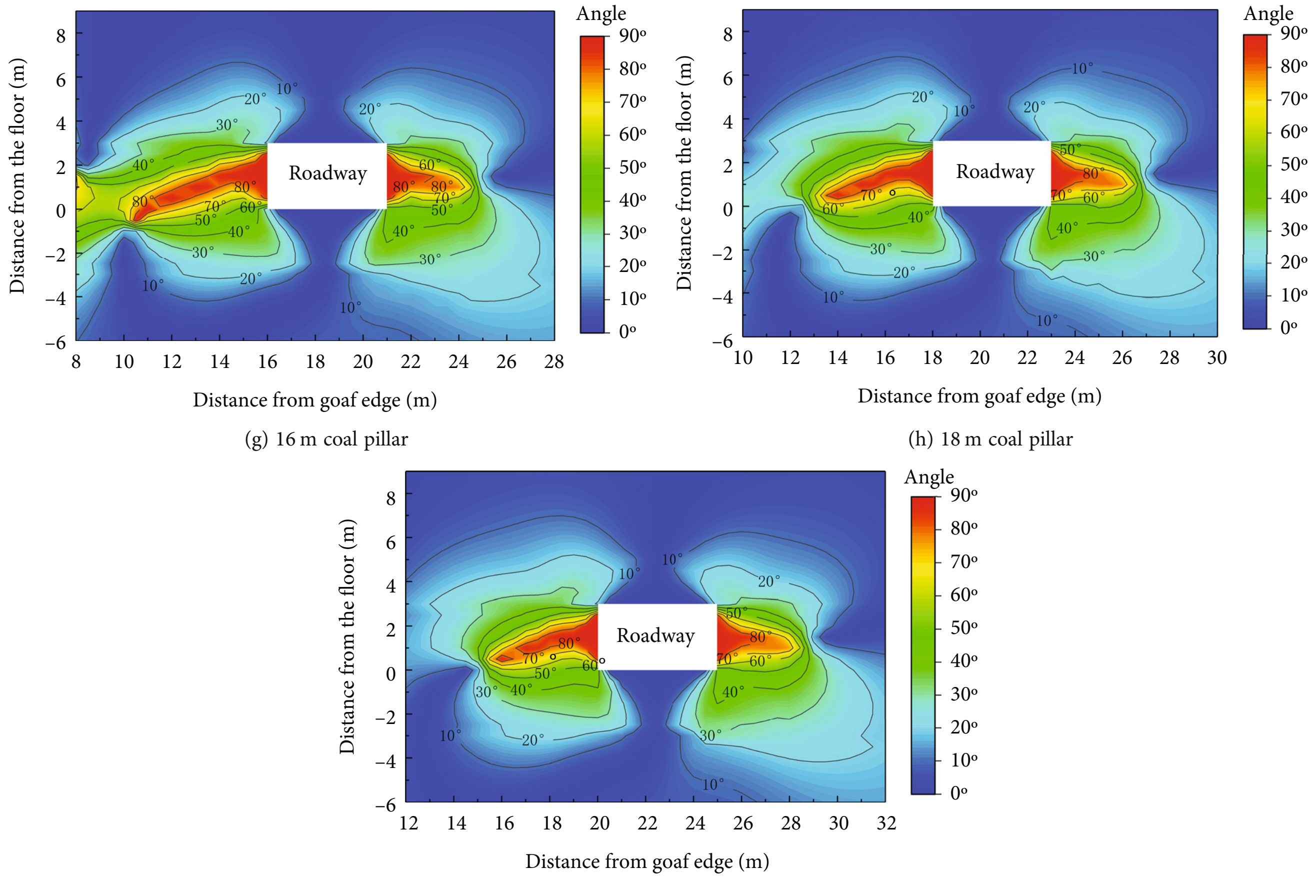


Figure 3: Layout of measuring line in principal stress direction of roadway surrounding rock.



(a) 4 m coal pillar
(b) 6 m coal pillar
(c) 8 m coal pillar
(d) 10 m coal pillar
(e) 12 m coal pillar
(f) 14 m coal pillar

Figure 4: Continued.



(g) 16 m coal pillar

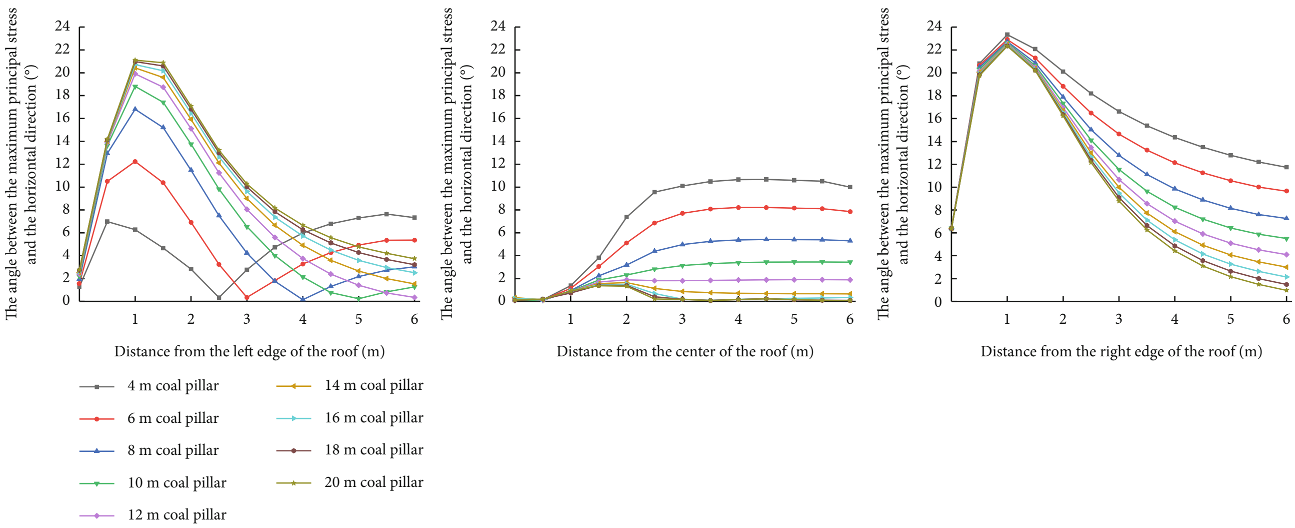
(h) 18 m coal pillar

(i) 20 m coal pillar

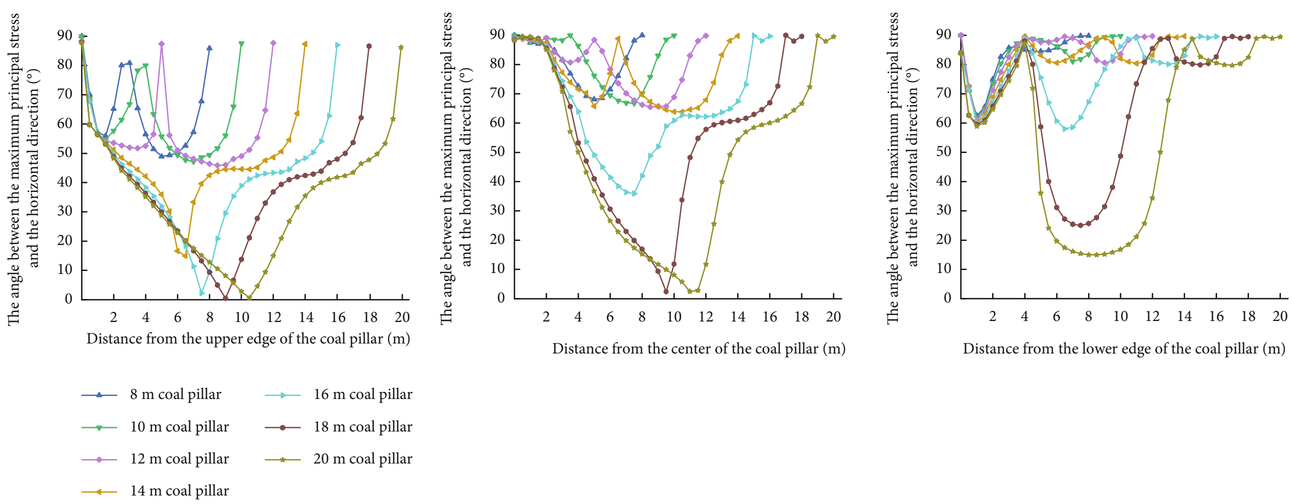
Figure 4: Angle cloud chart of maximum principal stress and horizontal direction of surrounding rock. (left side is coal pillar, right side is coal wall).

be seen that the distribution characteristics of the maximum principal stress direction in the roadway surrounding rock change significantly under different coal column widths. For the roof, the maximum principal stress is mainly in the horizontal direction, and the minimum principal stress is mainly in the vertical direction; with the increase of the width of the coal pillar, the maximum principal stress of the overlying rocks near the coal pillar side and the coal wall side of the top slab has a tendency to deflect in the vertical direction, and the direction of the maximum principal stress of the overlying rocks in the middle of the top slab has no obvious deflection. For the coal pillar wall, with the increase of the width of the coal pillar, the direction of the maximum principal stress is obviously deflected, when the width of the coal pillar is 4 m~14 m, the maximum principal stress of the whole coal pillar is mainly in the vertical direction, and the minimum principal stress is mainly in the horizontal direction, when the width of the coal pillar is 16 m~20 m, the maximum principal stress within 4 m from the edge of the roadway is mainly in the vertical direction, and the maximum principal stress within 4~6 m from the edge of the roadway is mainly in the horizontal direction. For the coal wall, the maximum principal stress direction does not change significantly with the change of coal pillar width, and the maximum principal stress at the edge of the coal wall is mainly in the vertical direction, while the maximum principal stress at the deep part of the coal wall gang is mainly in the horizontal direction. For the floor, when the width of coal pillar is 4 m, the maximum principal stress is mainly in the vertical direction near the pillar side and in the horizontal direction near the coal wall side; when the width of coal pillar is 6 m~20 m, the maximum principal stress is mainly in the horizontal direction, and with the increase of the width of coal pillar, the direction of the maximum principal stress is not significantly deflected.

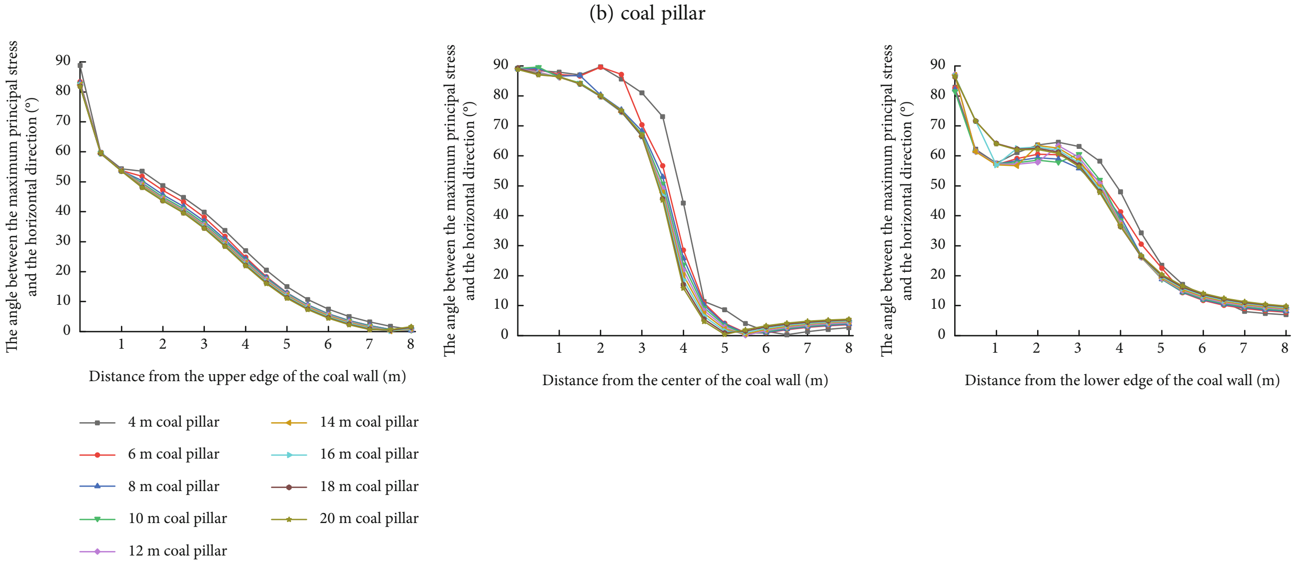
Figure 5 shows the curves of the maximum principal stresses, which are at different locations of road roof and floor and two surrounding rocks under different coal pillar widths with respect to the angle in the horizontal direction. From the above analysis, it can be seen that the 4 m and 6 m coal pillars are in plastic damage state, so no further analysis will be made here. By comparing the variation characteristics of the maximum principal stress direction in Figure 5 with the direction of the original rock stress field, it is obtained that the variation law of the maximum principal stress direction in the roadway surrounding rock area



(a) roof

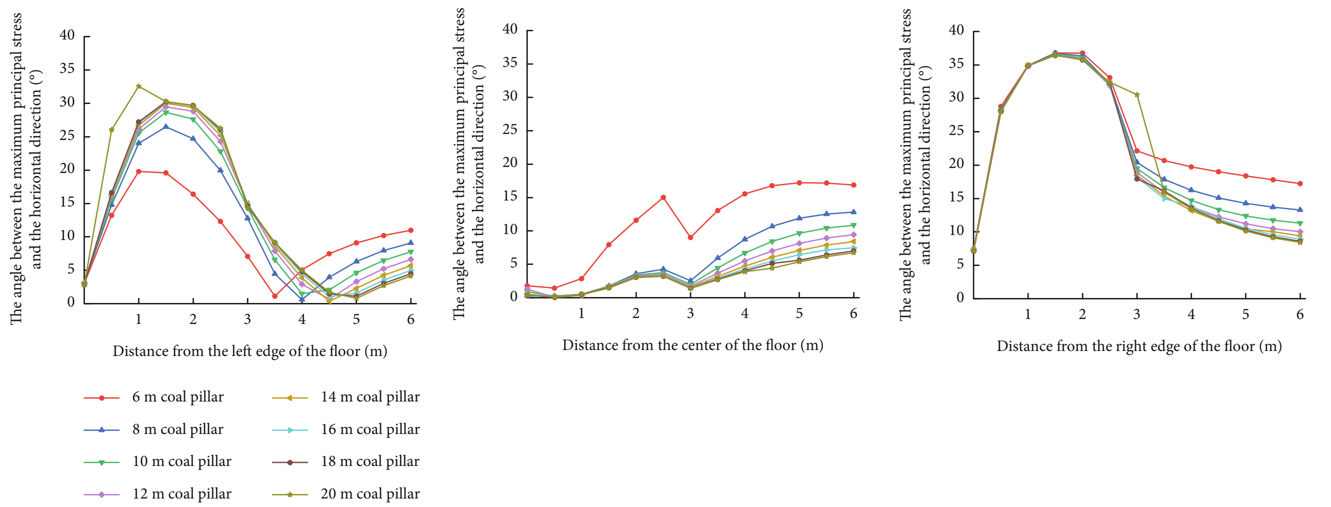


(b) coal pillar



(c) coal wall

Figure 5: Continued.



(d) floor

Figure 5: Variation curve of maximum principal stress direction of surrounding rock.

Table 3: The maximum principal stress deflection law of surrounding rock in roadway excavation.

Surrounding rock location	Deflection pattern
Roof	Continuous deflection in the vertical direction, but the degree of deflection is weak. Degree of deflection angle change: both sides of the roof > middle of the roof.
Coal pillar	The deflection is in the vertical direction, and the degree of deflection is decreasing. The degree of deflection from the edge of the coal pillar to the middle of the coal pillar shows “strong-medium-weak” transition. Degree of deflection angle change: middle of coal pillar > edge of coal pillar.
Floor	Continuous deflection in the vertical direction, with medium deflection at the position of 1.5 m~2 m under both sides of the floor, and weak deflection at other depth positions and the middle of the floor. Degree of deflection angle change: both sides of the floor > the middle of the floor.
Coal wall	All deflected in the vertical direction and the degree of deflection did not change significantly. The degree of deflection from the edge of the coal wall to the deep part of the solid coal shows “strong-medium-weak” transition. Degree of deflection angle change: middle of coal wall > edge of coal wall.

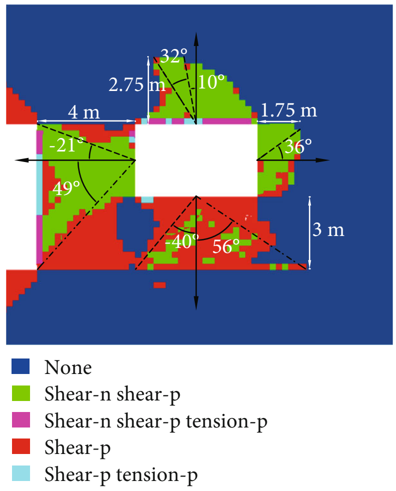
with the coal pillar width is shown in Table 3. (According to the deflection angle, three deflection degrees are defined: ① Weak: ≤30°; ② Medium: 30° ≤ 60°; and ③ Strong: ≥60°).

From the above analysis, it can be seen that the maximum principal stresses in the stress field of the roadway enclosure area are deflected in the vertical direction, but the deflection of the maximum principal stresses at different locations in the roadway enclosure has different sensitivities to the width of the coal pillar, resulting in the variability of the coal pillar width effect of the deflection of the principal stresses at different locations in the roadway enclosure.

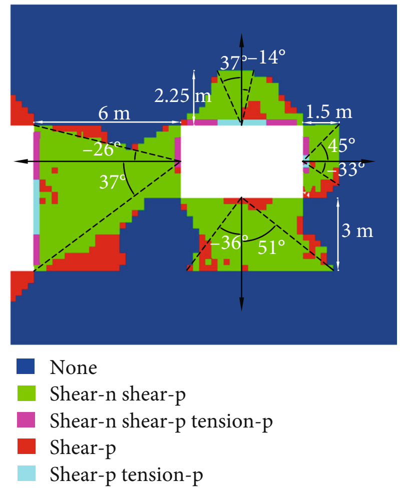
(1) For the roof and floor, the sensitivity of the maximum principal stress deflection at the position of the roof and floor near the two sides of the roadway to the width of the coal column is stronger. With the increase of coal pillar width, the maximum principal stress deflection angle changes obviously (maximum change of 20°) on both sides of the roof and floor, and the change is smaller (maximum change of 8°) in the middle position. Therefore, the maximum principal stress deflection in the roof and floor near the edge of the two gangs has an obvious coal pillar width effect, while the coal pillar width effect in the middle position is weaker

(2) For the coal pillar, the sensitivity of the maximum principal stress deflection inside the coal pillar to the change of the coal pillar width is stronger. With the increase of coal pillar width, the change of maximum principal stress deflection angle inside the coal pillar is obvious (maximum change of 70°), and the change of edge position is relatively small (maximum change of 12°). Therefore, the maximum principal stress deflection inside the coal pillar has obvious coal pillar width effect, while the coal pillar width effect of edge position is weaker

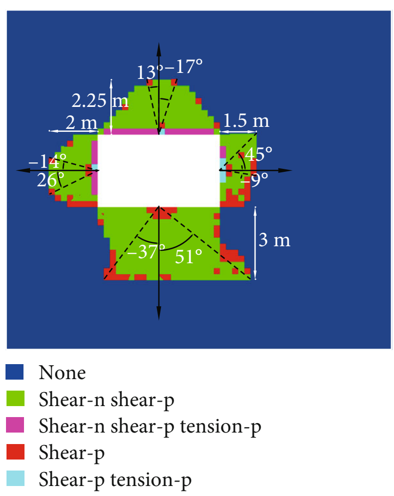
(3) For the coal wall, the sensitivity of the maximum principal stress deflection of the coal wall to the coal pillar width is weaker. With the increase of coal pillar



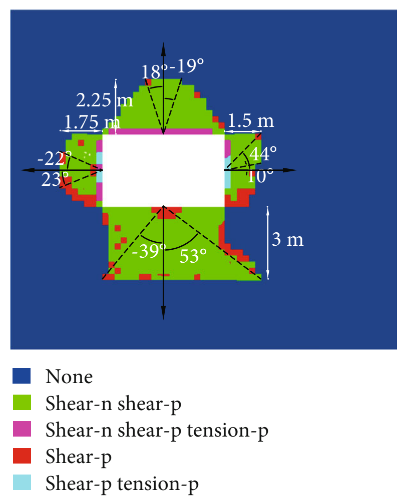
(a) 4 m coal pillar



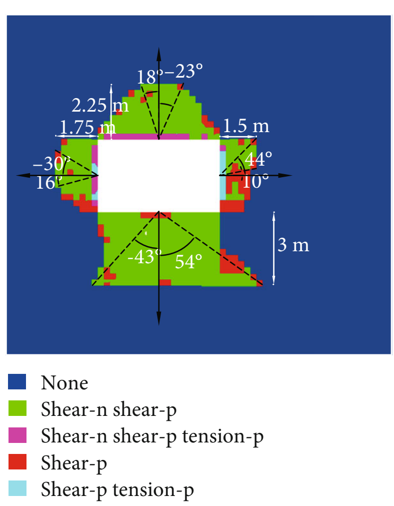
(b) 6 m coal pillar



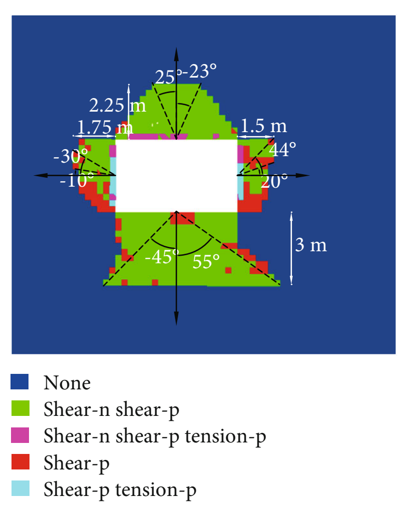
(c) 8 m coal pillar



(d) 10 m coal pillar

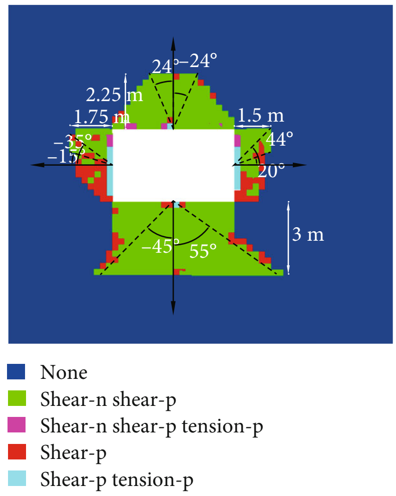


(e) 12 m coal pillar

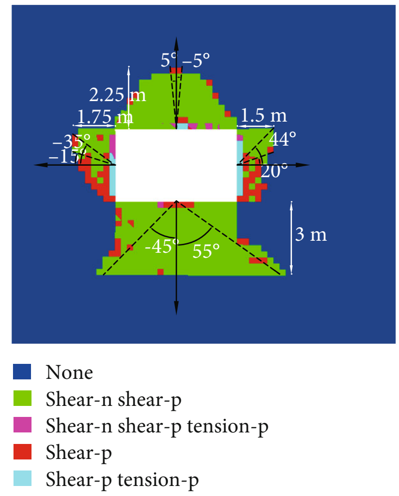


(f) 14 m coal pillar

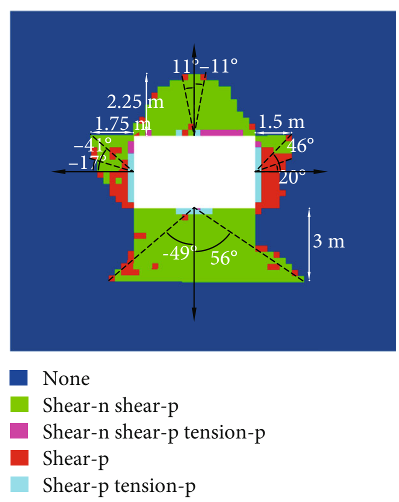
FIGURE 6: Continued.



(g) 16 m coal pillar



(h) 18 m coal pillar



(i) 20 m coal pillar

Figure 6: The form distribution of plastic zone of roadway surrounding rock. (left side is coal pillar, right side is coal wall).

width, the change of coal wall maximum principal stress deflection angle is small (maximum change 15°). Therefore, the coal pillar width effect of coal wall maximum principal stress deflection is weaker

3.3. Coal Pillar Width Effect of Plastic Zone Form of Roadway Surrounding Rock. Figure 6 shows the distribution of the plastic zone form in the surrounding rock of the roadway under different coal pillar widths obtained by numerical simulation. For the convenience of analysis, two indicators, plastic zone maximum damage depth and plastic zone maximum damage depth location, are defined to characterize the plastic zone form, where the plastic zone maximum damage depth location is expressed by the angle between the plastic zone maximum damage depth boundary and the centerline of the top and bottom plates of the roadway and the two sides of the gang, and the counterclockwise direction is specified as positive. From Figure 6, it can be seen that with the increase of coal pillar width, the plastic zone form of the roadway surrounding rock changes to different degrees. For the roof, the maximum damage depth of plastic zone is 2.75 m, when the width of coal pillar is 4 m, and the position of the maximum damage depth (10°~32°) is close to the roof of coal pillar side. When the width of coal pillar is 6 m~20 m, the maximum damage depth of plastic zone decreases to 2.25 m and remains unchanged, but its position is deflected to clockwise direction (solid coal side) when the width of coal pillar is 6 m~14 m, and it is not deflected when the width of coal pillar is 16 m~20 m. The form of the plastic zone is symmetric about the centerline of the roof. For the coal pillar, when the width of coal pillar is 4 m~6 m, the whole coal pillar is in the plastic damage state; when the width of coal pillar is 8 m~20 m, the coal pillar is no longer in the plastic damage state completely, and the maximum damage depth of the plastic zone does not change significantly, which is about 1.75 m, but the position of the maximum damage depth of the plastic zone continues to deflect in the clockwise direction (roof direction) with the increase

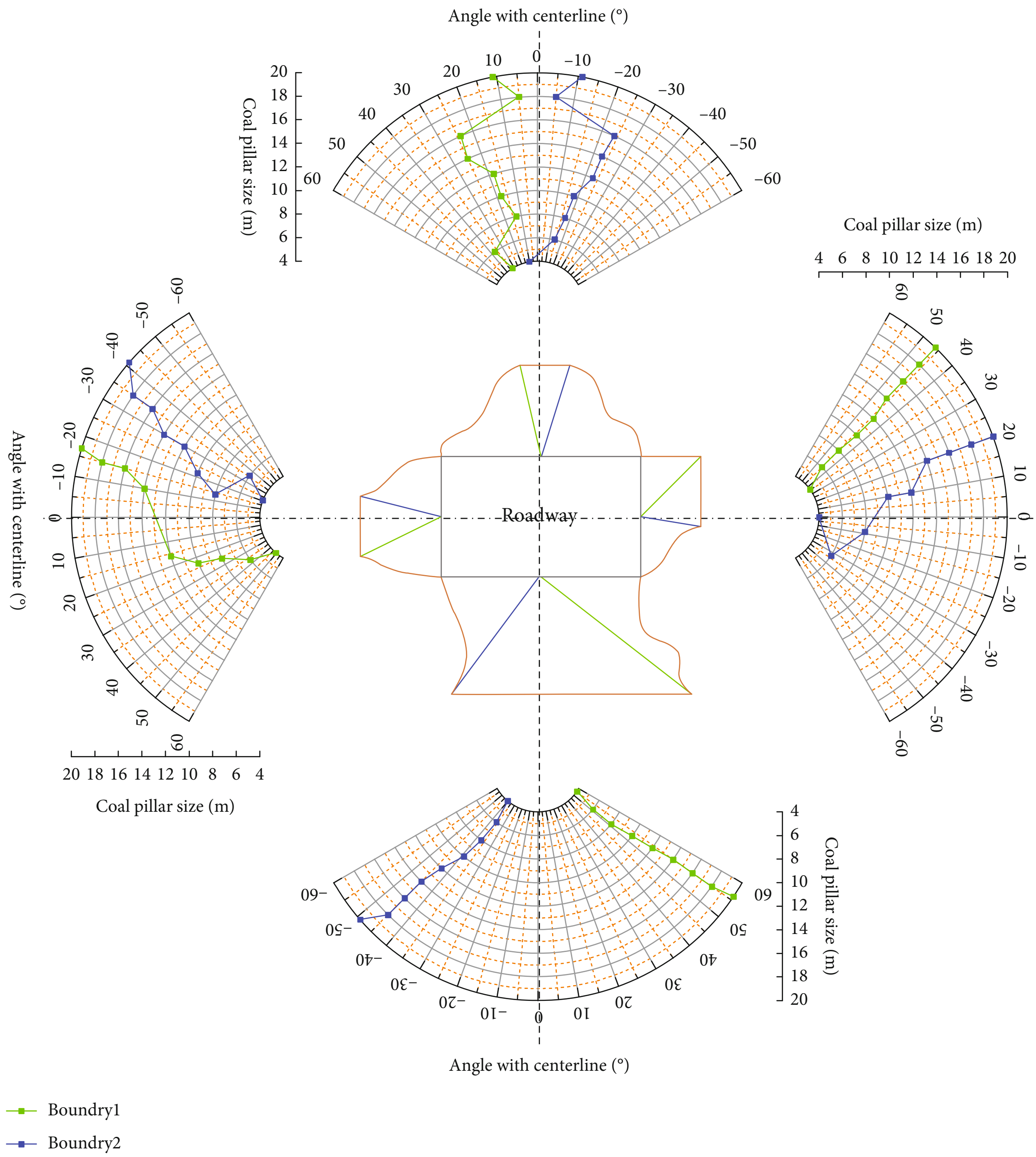


Figure 7: Location of maximum failure depth in plastic zone of roadway surrounding rock.

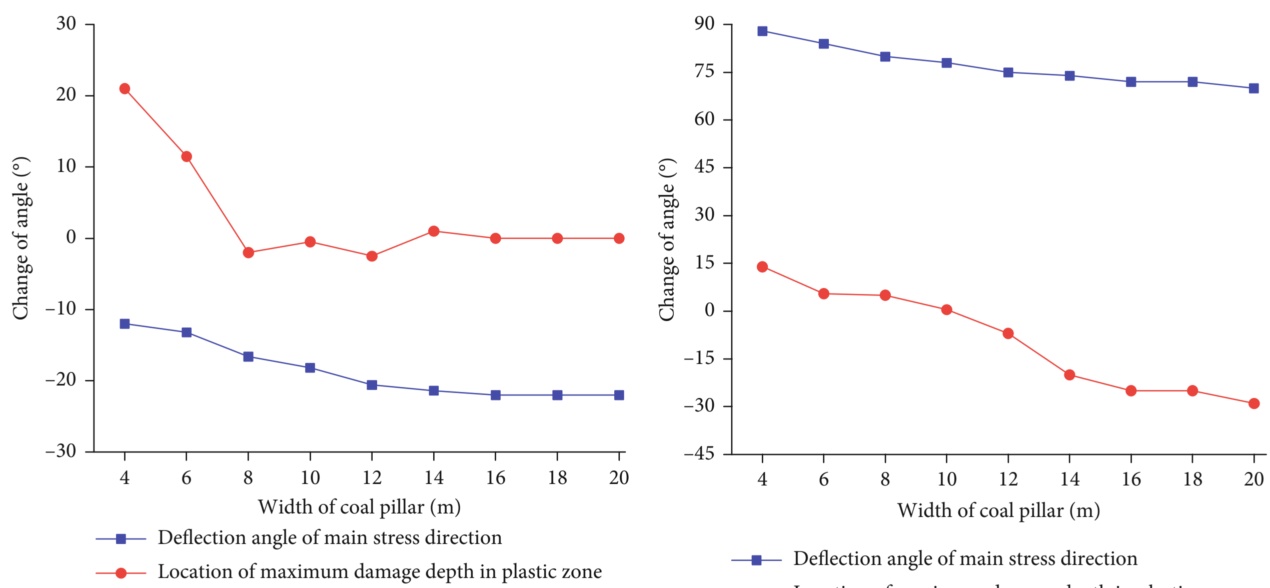
of the width of coal pillar. For the coal wall, when the width of coal pillar is 4 m, the maximum damage depth of plastic zone is 1.75 m, and the position of maximum break depth is 0°~36°. When the width of coal pillar is 6 m~14 m, the maximum damage depth of plastic zone decreases to 1.5 m and remains unchanged, but its position deflects significantly in the counterclockwise direction (roof direction). When the width of coal pillar is 16 m~20 m, the distribution of the plastic zone does not change significantly. For the floor, the maximum damage depth of the plastic zone does not change with the increase of coal pillar width, which is 3 m, and the location of the maximum damage depth also does not change significantly, and the form of the plastic zone is approximately symmetrical about the center line of the floor.

From the analysis of Figure 7 and Table 4, it can be seen that the form of plastic zone in different locations of the roadway surrounding rock shows different sensitivity to the change of coal pillar width, which leads to the variability of the coal pillar width effect of the form of plastic zone in different locations of the roadway surrounding rock.

From the above analysis, it can be seen that the plastic zone form at different locations of the roadway surrounding rock shows different sensitivities to the changes of coal pillar

Table 4: The variation law of the maximum failure depth position in plastic zone pillar.

	Width of coal pillar	Deflection direction	Deflection angle
Roof	4 m~8 m	Coal wall	10°~13.5°
	8 m~12 m	Coal wall	2°~2.5°
	12 m~16 m	Coal pillar	1°~1.5°
	16 m~20 m	No change	0°
	Width of coal pillar	Deflection direction	Deflection angle
Coal pillar	4 m~12 m	Roof	0.5°~8.5°
	12 m~16 m	Roof	10°~13°
	16 m~18 m	No change	0°
	18 m~20 m	Roof	4°
	Width of coal pillar	Deflection direction	Deflection angle
Floor	4 m~8 m	Coal pillar	0.5°~6.5°
	8 m~10 m	No change	0°
	10 m~14 m	Coal pillar	0.5°~1.5°
	14 m~20 m	No change	0°
	Width of coal pillar	Deflection direction	Deflection angle
Coal wall	4 m~6 m	Floor	12°
	6 m~10 m	Roof	10°~12°
	10 m~14 m	Roof	3°~5°
	14 m~20 m	No change	0°



(a) roof

(b) coal pillar

Figure 8: Curve of maximum failure depth position and principal stress direction in plastic zone of roadway surrounding rock.

width, which leads to the variability of the coal pillar width effect of the plastic zone form at different locations of the roadway surrounding rock.

(1) For the roof, when the width of coal pillar is less than 8 m, the sensitivity of the top plastic zone form to the change of coal pillar width is stronger, and with the increase of coal pillar width, the maximum damage depth of plastic zone decreases significantly, and the position of the maximum damage depth of plastic zone continues to deflect toward the coal wall, and the top plastic zone form has obvious coal pillar width effect. When the width of coal pillar is greater than 8 m, the sensitivity of roof plastic zone form to coal pillar width change is weak, with the increase of coal pillar width, the maximum damage depth of

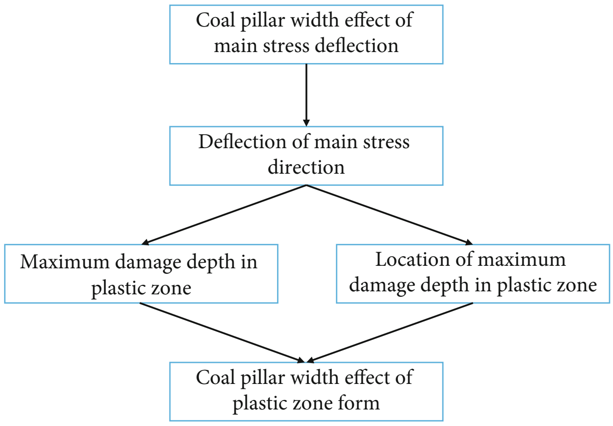


FIGURE 9: Formation mechanism of coal pillar width effect.

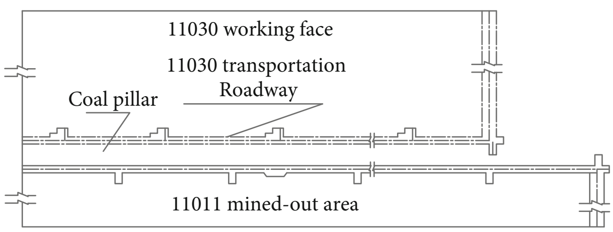


FIGURE 10: The layout plan of carrying roadway along 11030 working face.

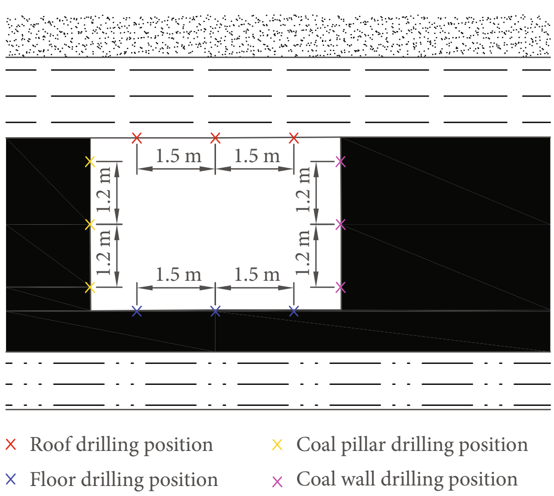


FIGURE 11: Borehole layout plan of transportation lane in 11030 working face.

plastic zone does not change obviously, its position change is small (maximum change 2.5°), and the coal pillar width effect of roof plastic zone form is weak

(2) For two sides of roadway, the form of plastic zone of two sides is sensitive to the change of coal pillar width. With the increase of coal pillar width, the maximum damage depth of plastic zone of coal pillar wall first decreases and then remains unchanged, and its position continues to deflect towards the roof. When the coal pillar width is less than 12 m, the maximum damage depth of the plastic zone of the coal wall first decreases and then remains unchanged, and its position first deflects to the floor direction and then to the roof direction. When the coal pillar width is greater than 12 m, the maximum damage depth and position of the plastic zone do not change significantly. The plastic zone form of two sides of roadway has obvious coal pillar width effect

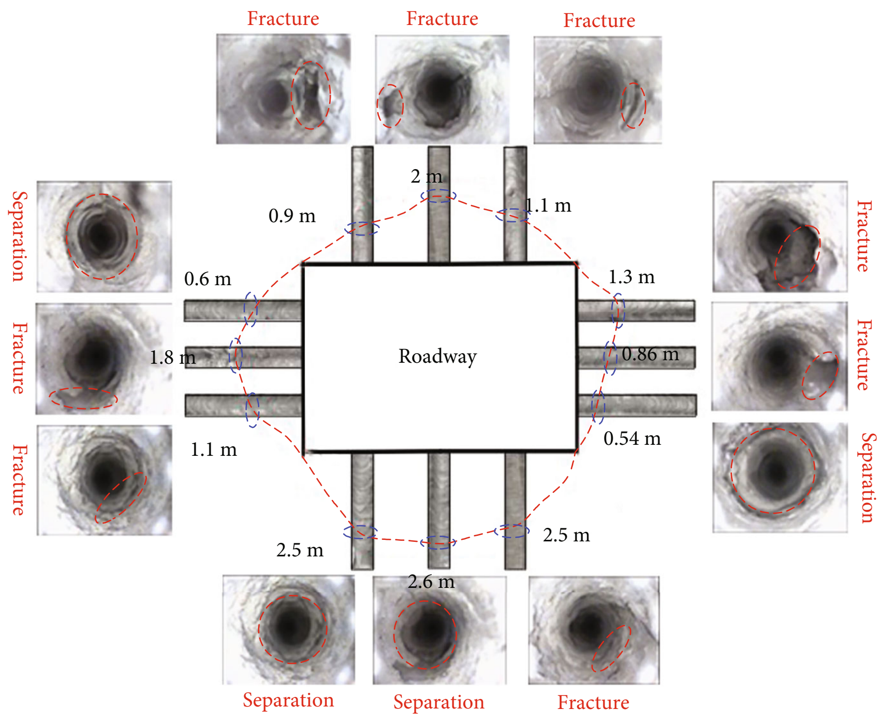
(3) For the floor, the form of the plastic zone of the floor is less sensitive to the change of the coal pillar width. With the increase of the coal pillar width, the maximum damage depth of the plastic zone does not change significantly, and its position changes slightly (the maximum change is 6.5°), and the coal pillar width effect of the form of the plastic zone of the floor should be weak

4. Analysis of the Stability of the Surrounding Rock Based on the Coal Pillar Width Effect

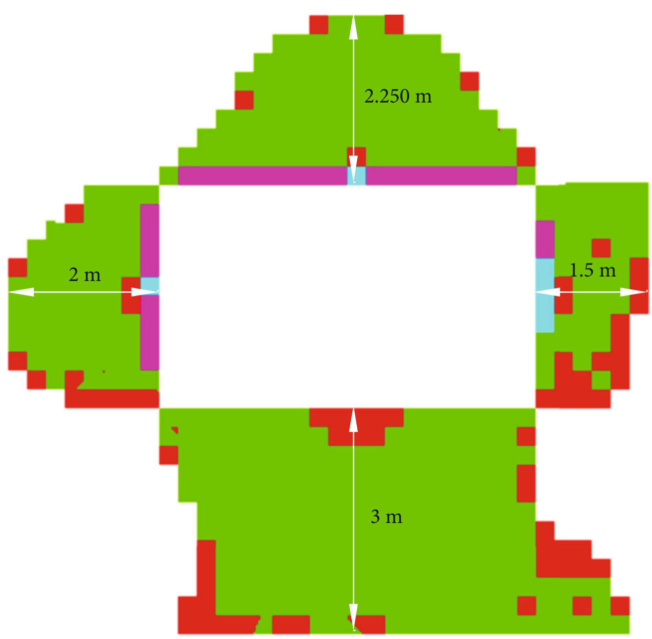
4.1. Mechanism of Coal Pillar Width Effect Formation. For the stability of roadway surrounding rock, the key is to ensure the stability of roadway roof and coal pillar. Therefore, based on the previous research results, taking the roadway roof and coal pillar wall as the research object, the author analyzes the variation law of the deflection angle of the main stress direction of roadway surrounding rock and the position of the maximum failure depth of plastic zone under different coal pillar widths and reveals the formation mechanism of coal pillar width effect in the plastic zone of roadway surrounding rock. Figure 8 shows the curves of the change in the deflection angle of the main stress direction and the position of the maximum damage depth in the plastic zone of the roadway roof and coal pillar at different coal pillar widths (the counterclockwise direction is specified as positive). From the figure, it can be seen that the position of the maximum damage depth in the plastic zone of the roadway surrounding rock and the angle of deflection of the main stress direction have approximately the same changing trend. As the width of coal pillar increases, the position of maximum damage depth and the direction of main stress in the plastic zone of the floor and coal pillar are deflected in the clockwise direction.

The width effect of the main stress deflection of the surrounding rock after the roadway excavation will cause the obvious deflection of the main stress direction of the surrounding rock, which will cause the maximum damage depth and location of the surrounding rock plastic zone to change, which results in the difference distribution of the plastic zone form of the surrounding rock, and which results in the shape of the surrounding rock plastic zone having the width effect of the coal pillar, as shown in Figure 9.

4.2. The Influence of Coal Pillar Width Effect on the Stability of the Surrounding Rock. According to the above study, influenced by the coal pillar width effect, the principal stress direction and plastic zone form at different positions of surrounding rock after roadway excavation will change to



(a) drill hole peeping results



(b) numerical simulation results

FIGURE 12: Comparison of the damage range of surrounding rock in 11030 transportation lane with the results of numerical simulation.

different degrees. For the roof, the deflection degree of the principal stress direction near the two sides of the roof is significantly greater than that in the central position, and the damage depth of the plastic zone at different positions of the roof is quite different, resulting in the difference in the stability of the surrounding rock on both sides and in the central position of the roof. For the coal pillar side, the deflection degree of the principal stress direction in the middle position of the coal pillar is significantly greater than that in the upper and lower sides, and the damage depth of the plastic zone in different positions is also different, resulting in a large difference in the stability of the surrounding rock in the middle and upper and lower sides of the coal pillar. Therefore, for roadways with different coal pillar widths, it is necessary to adopt different control measures for different positions of roof and coal pillar to ensure the stability of surrounding rock. Taking the 11030 working face transportation roadway of Zhaogu No. 2 Mine as an example, the

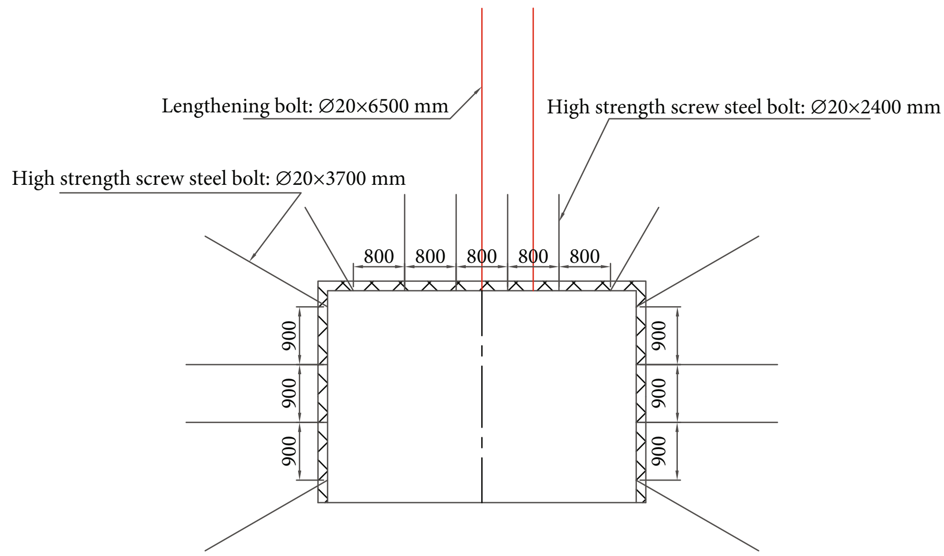


Figure 13: Section diagram of supporting design parameters for 11030 working face transportation roadway.

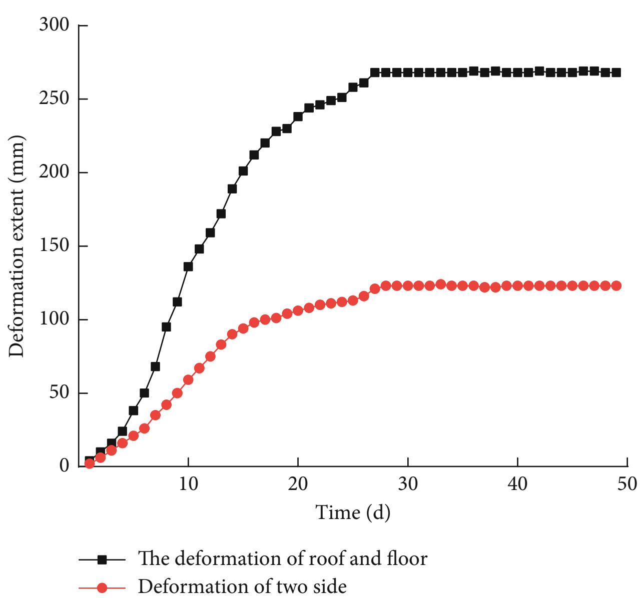


Figure 14: Change of surface displacement of roadway.

stability of roadway surrounding rock is analyzed combined with the width effect of coal pillar, which provides basic guidance for the stability control of roadway surrounding rock. For the roof, the maximum principal stress is mainly in the horizontal direction, but affected by the width effect of coal pillar, and the maximum principal stress on both sides of the roof tends to change in the vertical direction. And the maximum damage depth of plastic zone is located in the middle of roof. Therefore, the stability of the surrounding rock in the middle of the roof is poorer than that on both sides. In order to prevent the roof falling accident of the roadway, it is necessary to reinforce and support the middle position of the roadway roof after the roadway excavation is completed. For the coal pillar, the maximum principal stress is mainly in the vertical direction, but affected by the width effect of coal pillar, and the maximum principal stress at the upper and lower sides of coal pillar changes significantly in the horizontal direction. And the maximum damage depth of plastic zone deflects to the roof direction. The comprehensive analysis shows that the stability of the upper and middle sides of the coal pillar is worse than that of the lower side. In order to prevent the failure and instability of the coal pillar, it is necessary to reinforce the surrounding rock of the middle and upper sides of the coal pillar after the roadway excavation.

5. Engineering Case

The transportation roadway of 11030 working face in Zhaogu No. 2 Mine was excavated along the coal seam roof, and 8 m coal pillar was left between it and the 11011 mined-out area (Figure 10). The roadway was designed as a rectangular section of 4.8 m × 3.3 m (width × height). During the excavation of the roadway, the roadway surrounding rock had a nonuniform large deformation, the section contraction was serious, the maximum subsidence of roof was about 428 mm, and the maximum displacement of two sides was about 270 mm.

5.1. Detection of Rock Surrounding Damage Areas. In order to master the surrounding rock damage of 11030 working face transportation roadway and compare with the numerical simulation results (Figure 6(c)), the JL-IDOI (A) intelligent borehole TV imager was used to peep the surrounding rock damage of the roadway. Three boreholes were arranged at the roof and floor of the roadway and the two sides at 260 m from the opening of the roadway in 11030 working face. A total of 12 boreholes were arranged, as shown in Figure 11, the diameter of the borehole was 32 mm, and the depth of the borehole was 4 m.

Figure 12 shows the comparison between the borehole peeping results of surrounding rock of 11030 transportation roadway and the plastic zone form of numerical simulation. The damage area of roadway surrounding rock is asymmetric. The damage depth of rock stratum in the middle of roof is large, and the coal body in the middle of coal pillar is seriously broken. The damage depth of rock stratum near the roof of coal wall is the largest, and the distribution range of floor rock stratum is relatively uniform. The nonuniform morphological characteristics of plastic zone of roadway surrounding rock are basically consistent with the results of borehole peeping.

5.2. Roadway Support Design. Combined with the field peeping results and previous research results, it can be seen that the section convergence of 11030 transport roadway during excavation is serious, and the surrounding rock deformation of roadway shows obvious nonuniform characteristics. Therefore, considering the influence of mining activities in the later stage of the roadway, the middle roof is reinforced and supported by the length enable bolt and the high strength screw steel bolt to prevent the roof from falling [20–22]. Two sides, by patching high strength thread steel anchor, prevent two sides due to excessive deformation and cross. Specific design parameters are shown in Figure 13.

5.3. Support Effect. In order to verify the stability of the surrounding rock of the roadway after reinforcement support, a measuring station was arranged at 260 m from the opening of 11030 transportation roadway to monitor the change of the roadway surface displacement. The monitoring results show that the maximum deformation of the top and bottom plates from 0 to 28d after the roadway was reinforced and supported and is 268 mm, and the maximum deformation of the two sides is 123 mm; the displacement of the surrounding rock of the roadway remains basically the same after 28 d after the roadway was reinforced and supported, and there is no significant increase, indicating that the surrounding rock of the roadway tends to be stable. The monitoring results of the roadway surface displacement are shown in Figure 14.

6. Conclusion

(1) The deformation of the surrounding rock in the deep roadway under different widths of the coal pillar does not show a direct correlation between the width of the coal pillar and the deformation of the surrounding rock (the larger the width of the coal pillar, the smaller the deformation of the surrounding rock in the roadway), and the deformation of the surrounding rock at different locations in the same section of the roadway shows a nonuniform distribution

(2) The maximum principal stress deflects to the vertical direction in the stress field of the surrounding rock of deep roadway excavation, but the deflection of the maximum principal stress at different positions of the surrounding rock of roadway has different sensitivity to the width of the coal pillar. The coal pillar width effect of principal stress deflection on both sides of the roof and floor and inside the coal pillar is obvious, and the coal pillar width effect of principal stress deflection in the middle of the roof and floor and the edge of the coal pillar and the coal wall are weak

(3) The plastic zone form of surrounding rock of deep roadway after excavation will show differential distribution characteristics due to the change of coal pillar width, and the plastic zone form of surrounding rock at different positions of roadway has different sensitivities to the change of coal pillar width, resulting in obvious coal pillar width effect of plastic zone form of roadway roof and two sides, and weak coal pillar width effect of plastic zone form of floor

(4) The principal stress in the surrounding rock area of deep roadway excavation will deflect to varying degrees, which affects the form of the plastic zone of the surrounding rock. The position of the maximum damage depth of the plastic zone is approximately the same as the principal stress deflection, and the width effect of the coal pillar will have different degrees of influence on the stability of the surrounding rock at different positions of the roadway

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 that there are no conflicts of interest including any financial, personal, or other relationships with other people or organizations.

Acknowledgments

This paper was supported by the National Natural Science Foundation of China (Grant no. 51804243).

References

[1] H. P. Xie, F. Gao, and Y. Ju, “Research and development of rock mechanics in deep ground engineering,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 34, no. 11, pp. 2161–2178, 2015.

[2] A. H. Wilson, “The stability of underground workings in the soft rocks of the coal measures,” *International Journal of Mining Engineering*, vol. 1, pp. 91–187, 1983.

[3] J. M. Galvin, B. K. Hebblewhite, and M. D. G. Salamon, “Australian coal pillar performance,” *ISRM News Journal*, vol. 4, pp. 33–38, 1996.

[4] A. Jaiswal and B. K. Shrivastva, “Numerical simulation of coal pillar strength,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 46, no. 4, pp. 779–788, 2009.

[5] T. P. Medhurst and E. T. Brown, “A study of the mechanical behaviour of coal for pillar design,” *International Journal of*

Rock Mechanics and Mining Sciences, vol. 35, no. 8, pp. 1087–1105, 1998.

[6] R. Wang, S. Yan, J. B. Bai, Z. Chang, and T. Zhao, "Theoretical analysis and study of the destabilization on damaged width of rib pillar in open-pit highwall mining," *Advances in Civil Engineering*, vol. 2019, no. 8, Article ID 6328702, p. 15, 2019.

[7] C. Xu, X. Li, K. Wang, C. Guo, Q. Fu, and Y. Ju, "Reasonable coal pillar width of protective layer during high-gas coal seams mining," *Journal of China University of Mining and Technology*, vol. 49, no. 3, pp. 445–452, 2020.

[8] L. S. Jiang, P. P. Zhang, L. J. Chen et al., "Numerical approach for goaf-side entry layout and yield pillar design in fractured ground conditions," *Rock Mechanics and Rock Engineering*, vol. 50, no. 11, pp. 3049–3071, 2017.

[9] H. J. Li, Q. T. Chen, Z. Y. Shu, L. Li, and Y. Zhang, "On prevention and mechanism of bed separation water inrush for thick coal seams: a case study in China," *Environmental Earth Sciences*, vol. 77, no. 22, p. ???, 2018.

[10] S. L. Yang, G. F. Song, and J. H. Yang, "An analytical solution for the geometric broken characteristics of the overlying strata and its physical modeling study in longwall coal mining," *Arabian Journal Of Geosciences*, vol. 13, no. 3, p. 139, 2020.

[11] X. Guo, Z. Zhao, X. Gao, X. Wu, and N. Ma, "Analytical solutions for characteristic radii of circular roadway surrounding rock plastic zone and their application," *International Journal of Mining Science and Technology*, vol. 29, no. 2, pp. 263–272, 2019.

[12] H. Basarir, I. F. Oge, and O. Aydin, "Prediction of the stresses around main and tail gates during top coal caving by 3D numerical analysis," *International Journal of Rock Mechanics and Mining Sciences*, vol. 76, pp. 88–97, 2015.

[13] Y. Li, N. Ma, and J. Ma, "Surrounding rock's failure characteristic and rational location of floor gas drainage roadway above deep confined water," *Journal of China Coal Society*, vol. 43, pp. 2491–2500, 2018.

[14] J. P. Zuo, J. T. Wang, and Y. Q. Jiang, "Macro/meso failure behavior of surrounding rock in deep roadway and its control technology," *International Journal of Mining Science and Technology*, vol. 6, no. 3, pp. 301–319, 2019.

[15] D. J. Xue, J. Zhou, Y. T. Liu, and L. Gao, "On the excavation-induced stress drop in damaged coal considering a coupled yield and failure criterion," *International Journal of Mining Science and Technology*, vol. 7, no. 1, pp. 58–67, 2020.

[16] J. Li, N. J. Ma, and Z. Q. Zhao, "Butterfly leaf type roof falling mechanism and control technology of mining gateway," *Coal Science and Technology*, vol. 45, no. 12, pp. 46–52, 2017.

[17] F. Pellet, M. Roosefid, and F. Deleruyelle, "On the 3D numerical modelling of the time-dependent development of the damage zone around underground galleries during and after excavation," *Tunnelling and Underground Space Technology*, vol. 24, no. 6, pp. 665–674, 2009.

[18] J. Li, X. B. Qiang, W. S. Wang, and F. Wang, "Distribution law of principal stress difference of deep surrounding rock of gob-side entry and optimum design of coal pillar width," *Tehnički Vjesnik*, vol. 26, no. 6, pp. 1743–1752, 2019.

[19] J. Li, "The coal pillar design method for a deep mining roadway based on the shape of the plastic zone in surrounding rocks," *Arabian Journal of Geosciences*, vol. 13, no. 12, p. 454, 2020.

[20] L. Giresini, M. L. Puppio, and F. Taddei, "Experimental pull-out tests and design indications for strength anchors installed in masonry walls," *Materials and Structures*, vol. 53, no. 4, p. 103, 2020.

[21] L. Ji, F. Jicheng, and Z. Shengkai, "Study on long and short bolt coordinate support technology of mine soft rock roadway," *Coal Science and Technology*, vol. 43, no. 3, pp. 17–21, 2015.

[22] W. Fei, L. Hongtao, and Z. Shengkai, "Yieldable technology of lengthened bolts for high-stress soft rock roadways," *Chinese Journal of Geotechnical Engineering*, vol. 36, no. 9, pp. 1667–1673, 2014.