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Pressure Relief and Bolt Grouting Reinforcement and Width Optimization of Narrow Coal Pillar for Goaf-Side Entry Driving in Deep Thick Coal Seam: A Case Study

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Abstract: Goaf-side roadway driving with narrow coal pillars could obviously improve coal resource recovery rates compared with traditional large, wide pillars, and this is pivotal to the sustainable development of underground mines. However, it is very difficult to control the stability of goaf-side roadway driving, especially in deep, thick coal seams with large and high working faces. In order to control the stability of goaf-side entry driving in working face 210106 of the deep and thick coal seam in Xinji No. 2 Coal Mine in Anhui Province of China, we carried out field investigations, theoretical calculations, numerical simulations, and an engineering practice to identify the main factors influencing the deformation of the surrounding rock in order to optimize the width of the narrow coal pillar and to propose countermeasures for goaf-side entry driving. Our results show that the main factors influencing deformation of the rock surrounding the roadways at working face 210106 in Xinji No. 2 Coal Mine include high ground stress, large mining height, thick sandstone in the roof, and the residual abutment pressure of the adjacent goaf. The results obtained from theoretical calculations, the numerical simulations, and the engineering practice indicate that a 5 m-wide coal pillar is relatively appropriate and feasible. The countermeasures of pressure relief by blasting roof cutting and bolt grouting reinforcement were carried out to control the stability for goaf-side entry driving. Field measurements indicated that deformations of goaf-side entry driving in deep, thick coal seams could be efficiently controlled. The maximum deformations of sidewall-to-sidewall and roof-to-floor were 100 mm and 350 mm, respectively.

Keywords: thick coal seam; narrow coal pillar; goaf-side entry driving; pressure relief; hollow grouting cable; grouting

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1. Introduction

Compared with traditional large, wide pillars of 15–40 m, goaf-side roadway driving with narrow coal pillars could not only improve coal recovery rates but also decrease the stress concentration in the coal pillar, which is pivotal for the sustainable development of underground mines. Goaf-side roadway driving is increasingly widely used in major mining areas in China [1–4]. However, it is difficult to control the stability of goaf-side roadway driving, especially with working faces at large mining heights in deep, thick coal seams because of high ground stress, which greatly restricts the application of goaf-side roadway driving in deep underground mines. Therefore, it is of great importance to optimize the width of narrow coal pillars and propose countermeasures for goaf-side entry driving for working faces at large mining heights in deep, thick coal seams.

When the working face is mined, the effect of the mining creates significant abutment pressure and the range and position of the broken and plastic zones of the rock surrounding the roadway undergo changes. This is the same as the effect of stratified mining of thick and medium-thick coal seams, whereby, after the working face is mined, decompression, pressurization, and pressure stabilizing zones are formed on the adjacent coal mass and a certain range of the caving zone. After the transfer of support pressure, the edge of the coal mass in a certain range is destroyed forming a broken zone of a certain width, and a stress reduction zone is generally formed within 0–7 m from the edge of the coal body, which creates very favorable conditions for the construction of goaf-side entry driving. The roadway is generally located in the stress reduction zone when narrow coal pillars are used. After roadway excavation, the narrow coal pillar is destroyed and the pressure is released, causing the coal pillar to move significantly toward the roadway. The coal mass on the other side of the roadway evolves from an elastic zone under high pressure to a fracture zone and zones. As the bearing pressure transfers to the deep part of the coal mass, the coal mass gradually shifts in the direction of the roadway [5–9].

Research on goaf-side entry driving in coal mines with narrow coal pillars has been carried out for decades, and a lot of experience has been obtained with the formulation of some theoretical results. Under specific conditions, the effect of retaining narrow coal pillars and controlling the surrounding rock can be ideal. According to the distribution of the stress field inside and outside the working face, Chen et al. (2021) proposed a method to determine the width of the coal pillar along the goaf. The coal pillar and roadway should be set in the stress field and provide support through the anchorage and intact parts of the coal pillar [10]. Shi et al. (2020) used a method combining a physical model test and numerical simulation to explore the movement law of the overlying strata, the failure mechanism, and the fracture evolution law relating to goaf-side entry driving in thick coal seams. Physical test results have shown that the cantilever beam is easy to develop above the coal pillar, resulting in large and strong stress concentrations. After the hanging roof strata are cut using a cutting line, a significant amount of the rock load acting on the coal pillar can be released [11]. Ma et al. (2020) used Henan Lugou Coal Mine as an example to comprehensively analyze the stress distribution characteristics of narrow coal pillars and the influence of coal pillar width on roadway deformation. Taking into consideration the stability of the coal pillars, roadway deformation, coal recovery rate, and other factors, the appropriate width for narrow coal pillars was determined. Two principles were proposed to maintain the stability of goaf-side entry retaining of top coal, namely strengthening the roof support to ensure the stability of top coal and strengthening the coal sidewall support structure to achieve collaborative control [12]. Zhang et al. (2018) studied the coal pillar failure mechanism by combining field tests and numerical simulations. It was concluded that the coal pillar could be divided into three zones: the broken, stable, and caving zones. The stable zone, which accounts for one-third of the width of the coal pillar, plays a decisive role in coal pillar failure [13]. According to the specific geological and technical conditions of the coal pillar in Daizhuang Coal Mine, Lv et al. (2012) adopted the combined support mode of left continuous thread high-strength bolts and low relaxation prestressed bolts, which ensured the safety of the roadway and improved the stability of the rock surrounding the roadway [14]. Ta et al. (2021) studied the stability of retaining coal pillars for goaf-side entry in gently inclined coal seams and studied the fracturing instability mechanism by combining theoretical analysis, numerical simulation, and field monitoring. The results showed that uneven horizontal stress was the internal cause of asymmetric deformation and the failure of inclined coal seam roadways [15]. Li et al. (2020) studied coal pillar width and control of the rock surrounding goaf-side entry in extra-thick coal seams by combining field tests and numerical simulations. The optimal coal pillar width was determined, and an effective support method was proposed [16]. Yang et al. (2014) used goaf-side entry driving in Qidong Coal Mine as the engineering background, analyzed the deformation characteristics and stress distribution of the surrounding rock, and proposed that anchor grouting combined support could effectively control the surrounding deformation of the roadway; this solution has achieved good social and economic benefits [17]. Li et al. (2021) used a simulation method to analyze the principal stress characteristics and displacement characteristics of the rock surrounding roadways after goaf-side entry driving with coal pillars of different widths and evaluated the stability of the roadway to determine the appropriate width for the coal pillar [18]. Liu et al. (2020) proposed that the stress distribution in narrow coal pillars should be calculated in sections. Based on the zoning and energy release characteristics, it was proposed that the coal pillar should avoid overlapping or intersecting the peak values of the equilibrium zone limit to ensure a sufficient elastic zone, and that the roadway should be located in the shear slip zone or medium-pressure relief zone to reduce the accumulation of elastic strain energy in the surrounding rock [19]. Cheng et al. (2021) took a narrow coal pillar supporting a roadway in Wangzhuang Coal Mine as the engineering background and proposed advanced deep-hole nonpenetrating directional presplitting blasting pressure relief technology. The influence of non-through fracture length on the presplitting effect was studied via numerical simulation. The results showed that as the length of the non-through fracture increased, vertical stress in the center of the coal pillar, deformation of the narrow coal pillar, and energy accumulation on the coal pillar gradually decreased. The vertical stress at the end of the working face increased as the length of the non-through crack increased. Field application and monitoring results showed that nonpenetrating directional presplitting blasting could effectively control the deformation of small pillars supporting the roadway [20].

Because it is affected by ground stress, roof and floor lithology, coal seam characteristics, and mining intensity, the deformation of rock surrounding the roadway in Xinji No. 2 Coal Mine is extremely sensitive. During roadway excavation and mining of the working face, there are many mine pressure phenomena such as anchor bolt or cable breakage, floor heave, strong displacement of the coal wall along the goaf, and severe subsidence of the shoulder angle, all of which have a significant influence on mine layout, production continuity, and support costs. There is a need for breakthroughs in the technology concerning surrounding rock control for goaf-side entry driving.

In order to control the stability of goaf-side entry driving at large mining height working face 210106 in the deep, thick coal seam in Xinji No. 2 Coal Mine of China Coal Xinji Energy Co., Ltd. in Anhui Province of China, field investigations, theoretical calculations, numerical simulation, and an engineering practice were carried out to identify the main factors influencing the deformation of the surrounding rock to optimize the width of narrow coal pillars and propose countermeasures for goaf-side entry driving.

2. Engineering and Geological Profiles of the Roadway

The width of the coal pillar in the main coal seam of Xinji No. 2 Coal Mine is 10–15 m, which has adverse effects on the resource recovery rate and safe production at the working face. Therefore, it is of great significance to study the appropriate coal pillar size for economic benefit, safety development, and the scientific and technological progress of China Coal Xinji Energy Co., Ltd.

2.1. Position of Working Face

The haulage roadway of working face 210106 is located in the mining district 2101 of the second level of the minefield, and the overall tendency is an NNE monoclinic structure, which is the haulage roadway of the second working face of coal group No. 1 in Xinji No. 2 Coal Mine. The coal seam occurrence is relatively stable within the recoverable range, and the overall structure is single with an average inclination of about 8°. The average mining thickness of the coal seam is 4.2 m. Therefore, the coal pillar between the haulage roadway of working face 210106 and the return air roadway of working face 210108 (the first mining face) is the first section coal pillar generated in coal group No. 1. The coal is transported uphill from mining district 2101 in the west, and close to the waterproof coal pillar line of the first coal group in the east. The north is adjacent to the goaf of the working face 210108, and the south is the unmoved area. The depth of the roadway is about 610 m. The recoverable strike length is 1242–1316 m and the inclined length is 150 m. The roadway layout of working face 210106 is shown in Figure 1. A 5 m-wide coal pillar for goaf-side entry driving was carried out between adjacent working faces 210106 and 210108 in Xinji

No. 2 Coal Mine, according to the results obtained from theoretical calculations and the numerical simulation of this research.

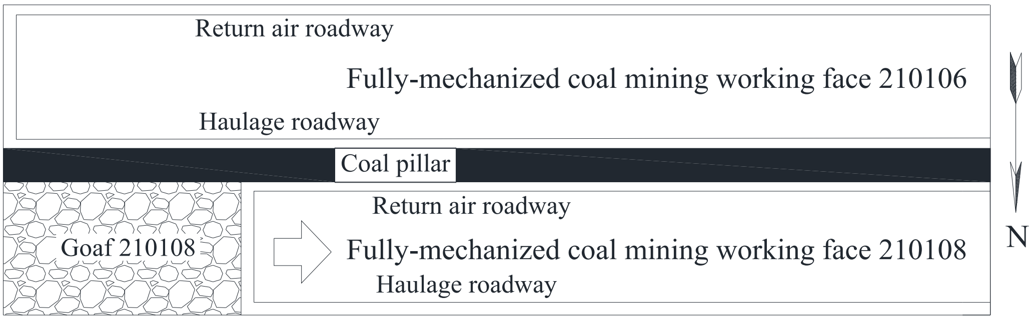


Figure 1. The roadway layout of working face 210106.

2.2. Occurrence Characteristics of Coal and Rock Strata

The geological structure of coal group No. 1 is relatively simple. According to the actual detection data, a layer of dark grey and grey-black gangue and mudstone often develop between coal seams, and their thickness is between 0 and 1.7 m with an average of 1.1 m. The immediate roof is siltstone with an average thickness of 6.0 m, and above this are medium to fine sandstone and fine sandstone. The immediate bottom is mudstone with an average thickness of 1.1 m, and beneath that is sand–mud interbed or mudstone. The lithology of the coal seam roof and the floor is shown in Table 1.

Table 1. Coal roof and floor lithology.

Name of Roof and Floor	Rock Name	Average Thickness	Rock Character
Basic roof	Medium-fine sandstone	27.1 m	Deep gray-gray, thin to medium-thick layer, fine sandstone band and siderite band, powder structure, mainly feldspar, quartz, mica, uniform bedding, fissure filling pyrite, calcite.
Immediate roof	Siltstone	6.0 m	Gray-white, medium-thick layer, medium-grained structure, quartz-dominated, feldspar followed, sorting medium-poor, local siderite, fracture development.
Immediate floor	Mudstone	1.1 m	Slime composition, containing charcoal, plant fossils.
Basic floor	Interbedded sandstone and mudstone or mudstone	12.8 m	Light to dark gray, thin, argillaceous, sandy composition, horizontal bedding, wavy bedding, containing muscovite, biotite, with biological disturbance structure, flat fracture.

3. Analysis of Roadway Support Difficulties

3.1. High Ground Stress

The depth of the haulage roadway of working face 210106 is about 610 m, and it belongs to the deep roadway. The vertical stress is about 15.25 MPa, the original rock stress is large, and the ground pressure is high. According to the results of in situ stress measurement in Xinji No. 2 Coal Mine, the ratio of maximum horizontal principal stress to vertical stress is up to 1.74. Horizontal tectonic stress has a significant influence on roadway excavation and has obvious directivity. The roadway is in a high-stress environment, and deformation of the surrounding rock shows mutual transformation between elasticity and plasticity rheological and expansion characteristics. At the same time, the rock surrounding the deep roadway is characterized by rapid deformation speed, long duration, asymmetric deformation, and a large range of loose and broken surrounding rock, which makes the surrounding rock control of the roadway very challenging.

3.2. Large Mining Height

The thick coal seam determines the mode of fully mechanized mining in working face 210106. The average mining height of working faces 210108 and 210106 was 4.2 m. The average daily mining progress was about 6.4 m. The average large mining height causes the height of the basic roof fracture to increase. The rotary subsidence of the key block to the edge of the coal pillar causes the concentration of stress on the coal side, which aggravates the development of the surrounding rock fracture and transfers from the shallow to the deep to form a large deformation of the surrounding rock.

3.3. Thick Sandstone in the Roof Stata

The roofs of coal group No. 1 in working face 210108 of Xinji No. 2 Coal Mine are thick sandstone with high strength, good integrity, and strong stability. After the working face is mined, often the roof does not automatically collapse and a large hanging area is exposed in the goaf resulting in a large periodic weighting step. The influence range of abutment pressure in advance of the working face is much larger than that of the general working face, which causes serious mine pressure behavior on the roadway in advance of the working face.

3.4. The Residual Abutment Pressure of Adjacent Goaf

The coal pillar is affected by multiple dynamic pressures, resulting in plastic fracturing. The bearing capacity of the coal pillar is greatly reduced. Affected by the stress disturbance of adjacent working face 210108 during roadway excavation and mining, and the residual abutment pressure of the goaf, the plastic zone of the haulage roadway roof and narrow coal pillar expands, deformation increases, and cracks develop and expand. The original rock stress zone in the coal pillar disappears, and the degree of damage intensifies and gradually becomes a plastic state of complete failure. Only residual strength is retained, and the bearing capacity decreases sharply. The above factors contribute to roadway support difficulties.

4. Theoretical Calculation of Narrow Coal Pillar Width of Goaf-Side Entry Driving

The goaf-side entry is a space composed of a coal seam roof and floor, solid coal, and a narrow coal pillar. The deformation and instability of any boundary will affect the overall stability of the roadway. According to the masonry beam theory, the roof structure for goaf-side entry is shown in Figure 2. Rock mass B is in a stable state before mining roadway excavation. After roadway excavation, the plastic failure of coal mass occurs under the action of lateral abutment pressure. The lateral abutment pressure is large, and the regional damage is serious [21,22]. Because of the influence of advanced abutment pressure on the working face, the coal mass in this area has secondary damage which can easily affect the stability of the masonry beam structure in the upper roof resulting in the sliding instability of rock mass B, which seriously threatens the stability of roadways along the goaf and narrow coal pillars.

The width of the coal pillar between adjacent the working faces of Xinji No. 2 Coal Mine is usually 10–15 m, which not only leads to the permanent retention of a large number of valuable coal resources underground but also means the roadway is located in the stress concentration area, which is not conducive to its long-term stability. Therefore, in order to reduce the loss of coal resources and the stress concentration in the rock surrounding the roadway and alleviate the tension of alternate mining and excavation in the working face, we decided to study the feasibility of using narrow coal pillar goaf-side entry driving technology to excavate the machine lane of working face 210106. The appropriate coal pillar width is the key factor determining the stability of the coal pillar and the successful completion of goaf-side entry driving. According to limit equilibrium theory and Figure 2, the best width for coal pillar B is calculated as follows.

$$B = X_1 + X_2 + X_3 \tag{1}$$

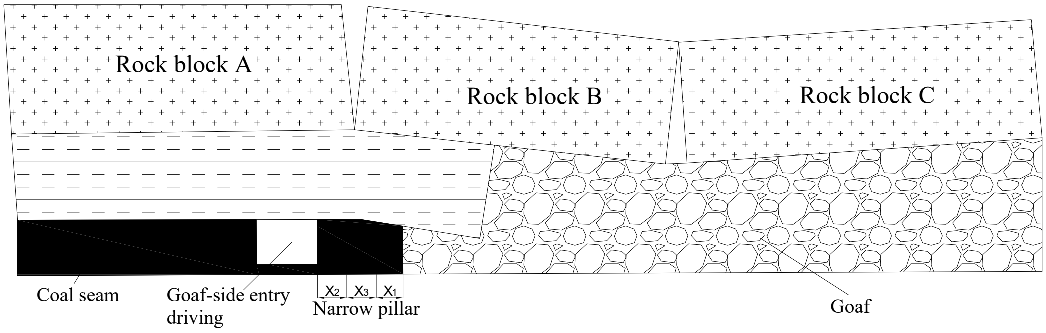


Figure 2. Roof rock structure of goaf-side entry driving.

In this formula, B is the narrow coal pillar width; X_1 is the width of the plastic zone produced in the goaf-side coal body after mining, that is, the width of the limit equilibrium zone which can be calculated according to the following Formula (2) [23,24]; X_2 is the length of the bolt, taken to be 2.0 m; and X_3 is the stability coefficient of the coal pillar considering the large thickness of the coal seam, which is calculated according to (X_1 + X_2)(10%–30%).

$$X_1 = \frac{mA}{2\tan\varphi}\ln\left[\frac{k\gamma H + \frac{C_c}{\tan\varphi}}{\frac{C_0}{\tan\varphi} + \frac{P_0}{A}}\right] \tag{2}$$

In this formula m is the average mining thickness of the coal seam, taken to be 4.2 m; A is the lateral pressure coefficient, $A = \mu/(1-\mu)$; Poisson's ratio $\mu = 0.3$, $A = 0.43$; φ is the internal friction angle of the coal seam interface, taken to be 30°; C_0 is the coal seam interface bonding force, taken to be 5 MPa; k is the stress concentration coefficient, taken to be 1.6; γ is the average bulk density of rock, taken to be 25,000 N/m^3; H is the depth of coal seam, taken to be 610 m; and P_0 is the support resistance to the coal side, taken to be 0.1 MPa.

According to the above conditions, we can obtain X_1 = 2.0 m and B = 4.4 m–5.2 m. In order to ensure that the anchorage section of the threaded steel anchor bolt is installed in a stable coal body, the width of the narrow coal pillar should be greater than 4.4 m.

Based on the production geological conditions of mining district 2101 in Xinji No. 2 Coal Mine, the appropriate width of the narrow coal pillar in the goaf-side entry driving of haulage roadway 210106 is 4.4–5.2 m by theoretical calculation.

5. Simulation Analysis of Narrow Coal Pillar Width for Goaf-Side Entry Driving

5.1. Establishment of Numerical Model

A numerical model was established by means of the Fast Lagrangian Analysis of Continua in three dimensions (FLAC3D 5.0) to optimize the width of the narrow coal pillar for goaf-side entry driving without the anchor support in working face 210106 of the deep and thick coal seam in Xinji No. 2 Coal Mine. The model size was 320 m × 50 m × 80 m, and the physical and mechanical parameters of each rock layer are shown in Table 2. The constitutive model of the Mohr–Coulomb yield criterion was adopted. The horizontal displacements of the model were fixed around its lateral sides, and the vertical displacement was fixed at the bottom. Vertical stress of 15.25 MPa (610 m) was applied to the top of the model to simulate the self-weight load of the rock stratum. The numerical simulation model is shown in Figure 3.

Table 2. Physical and mechanical parameters of the numerical simulation experiment.

Strata	Density (kg·m^{-3})	Thickness (m)	Bulk Modulus K (GPa)	Shear Modulus G (GPa)	Cohesion C (MPa)	Internal Friction Angle (°)
Moderate-coarse sandstone	2700	7.2	4.1	2.6	4.0	38
Siltstone	2760	5.6	4.4	2.6	3.5	40
Moderate-coarse sandstone	2700	8.6	4.1	2.6	4.0	38
Fine sandstone	2660	10.5	3.0	2.8	3.1	35
Medium-fine sandstone	2740	8.0	4.1	2.6	4.1	40
Siltstone	2760	6.0	4.4	2.6	3.5	40
No. 1 coal (upper)	1410	4.2	0.9	0.5	0.7	36
Mudstone	2700	1.1	1.2	0.9	0.7	24
No. 1 coal	1410	3.5	0.9	0.5	0.7	36
Mudstone	2700	1.1	1.2	0.9	0.7	24
Shaly sandstone	2600	11.7	2.8	0.56	2.4	35

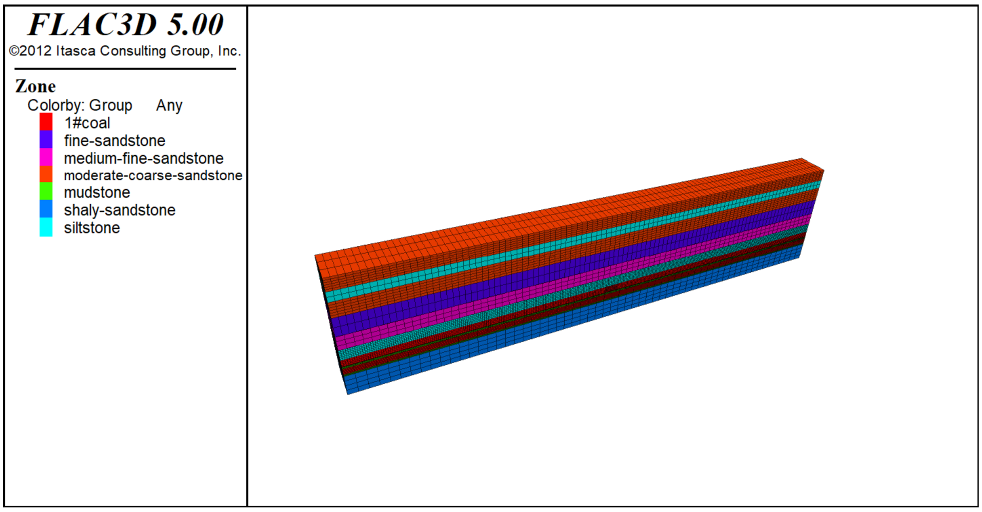
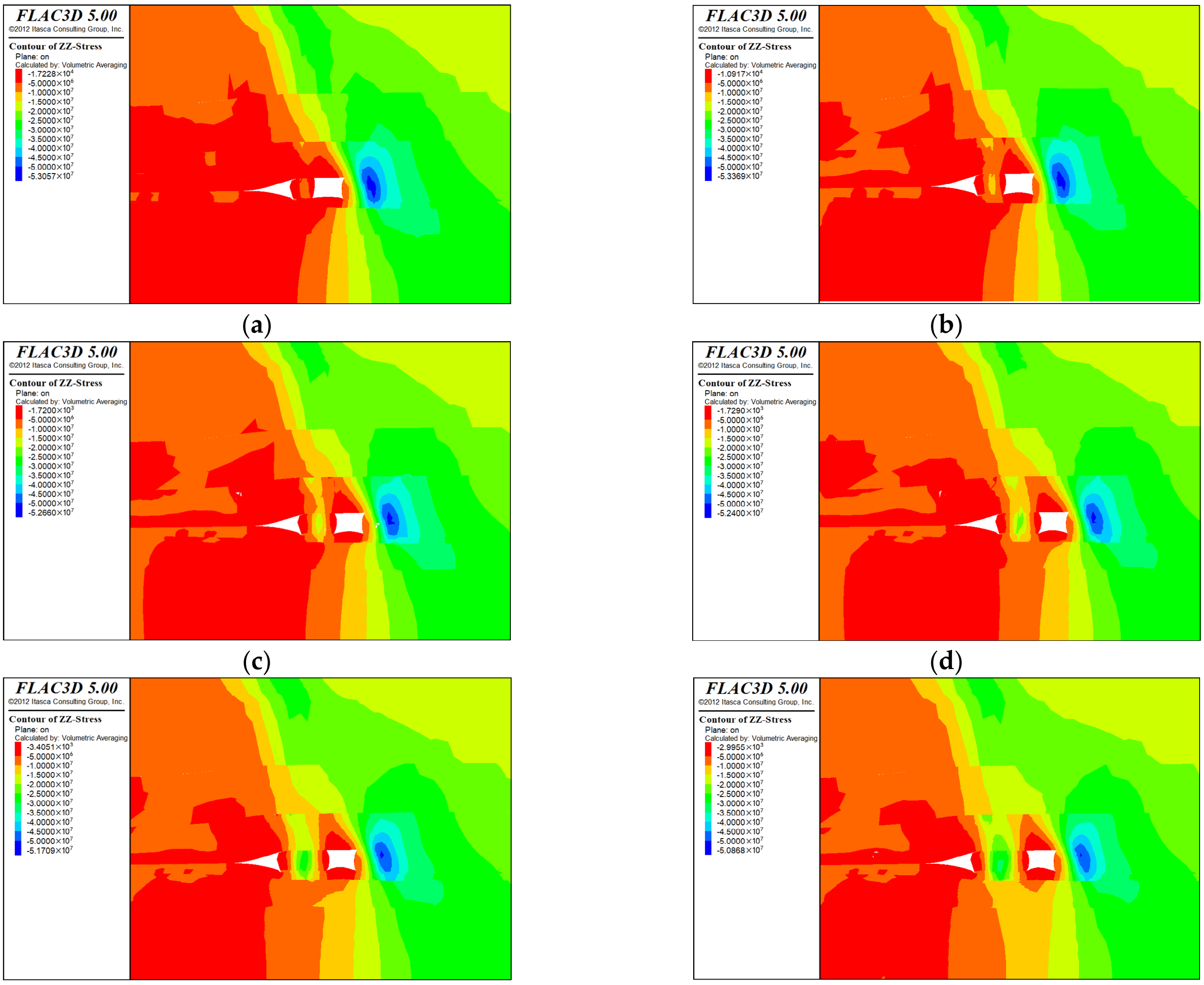


Figure 3. Numerical simulation model.

5.2. Vertical Stress Distribution

In order to reflect the stress distribution of the rock surrounding the roadway under different coal pillar widths, we simulated the stress distribution of the rock surrounding the roadway and the coal pillar during excavation of the haulage roadway 210106 [25,26]. A vertical stress nephogram of the rock surrounding the roadway under different coal pillar widths is shown in Figure 4, and a vertical stress distribution diagram of the narrow coal pillar is shown in Figure 5.

When the width of the coal pillar is 3 m or 4 m, the stress on the narrow coal pillar is less than the original rock stress, the coal mass is seriously broken, and the bearing capacity is very low. When the coal pillar width is 5–7 m, the coal pillar begins to show stress concentration, there is a stable bearing area of a certain width in the coal pillar, and the coal mass has a certain bearing performance. When the coal pillar width is greater than 8 m, the degree of stress concentration on the coal pillar increases significantly (the stress concentration coefficient is 2.1) and the stress environment of the rock surrounding the roadway deteriorates, which is not conducive to the control of the rock surrounding the roadway. Therefore, an appropriate coal pillar width is 5–7 m.



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 4. Stress distribution nephogram of rock surrounding the roadway under different coal pillar widths (Unit: Pa): (**a**) 3 m; (**b**) 4 m; (**c**) 5 m; (**d**) 6 m; (**e**) 7 m; (**f**) 8 m.

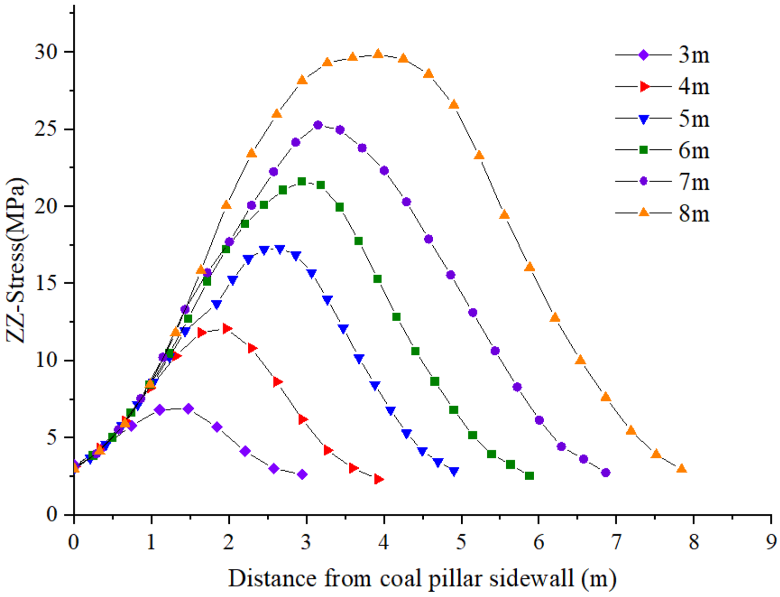
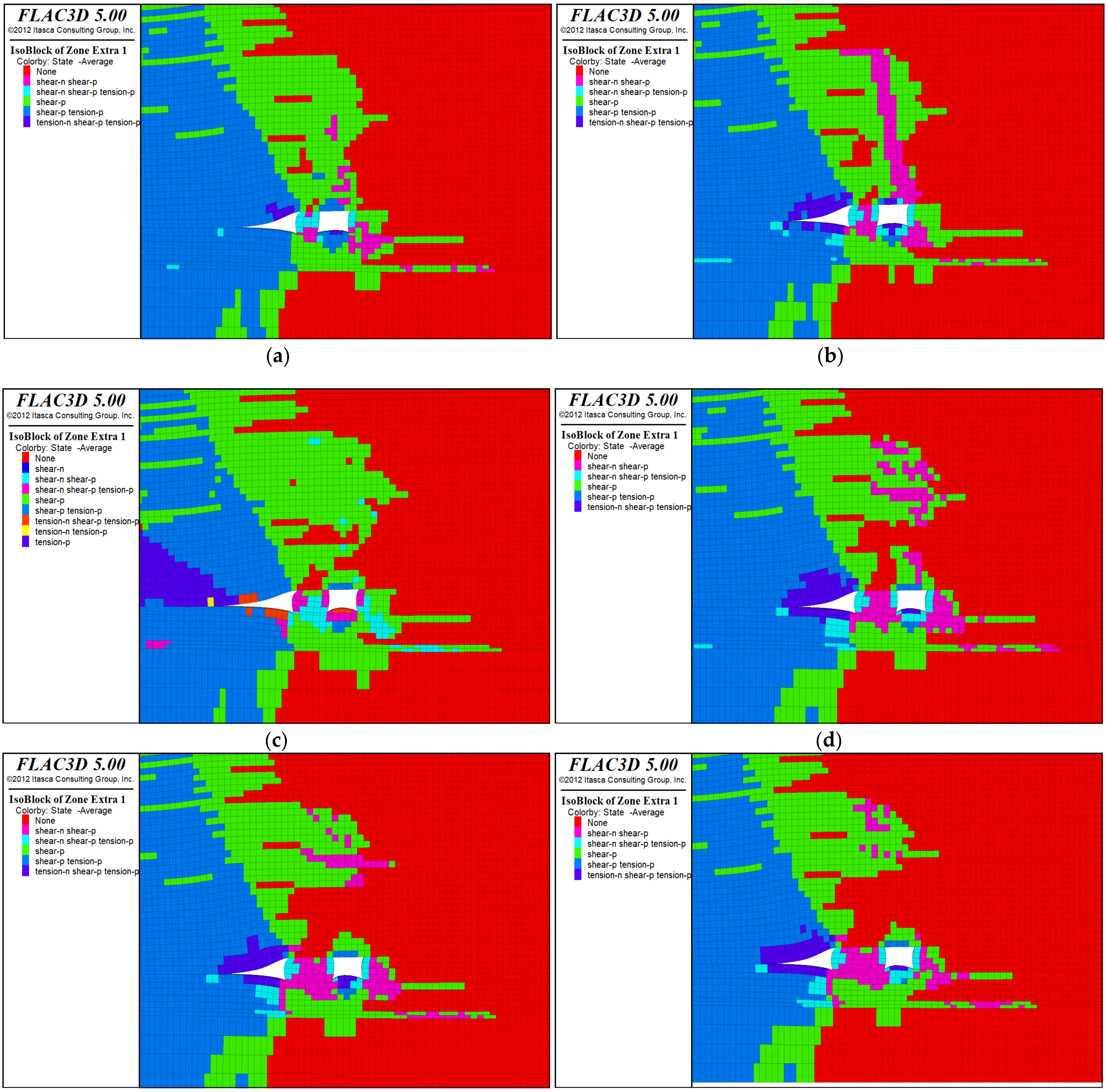


Figure 5. Vertical stress distribution map of the narrow coal pillar.

5.3. Plastic Zone Distribution

In order to reflect the plastic zone distribution of rock surrounding the roadway under different coal pillar widths, we simulated the plastic zone distribution of the roadway-surrounding rock and the coal pillar during excavation of the haulage roadway 210106. The distribution of the plastic zone under different coal pillar widths is shown in Figure 6.



(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

Figure 6. Plastic zone distribution of the surrounding rock of the roadway under different coal pillar widths: (**a**) 3 m; (**b**) 4 m; (**c**) 5 m; (**d**) 6 m; (**e**) 7 m; (**f**) 8 m.

When the coal pillar width is 3 or 4 m, the roadway is completely located in the plastic zone generated by the mining of the adjacent working face, and when the coal pillar width is greater than 5 m, the plastic zone of the rock surrounding the roadway begins to separate from the plastic zone generated by the mining of the adjacent working face. As the coal pillar width increases, the plastic zone of the roadway roof gradually decreases. Therefore, an appropriate coal pillar width should be greater than 5 m.

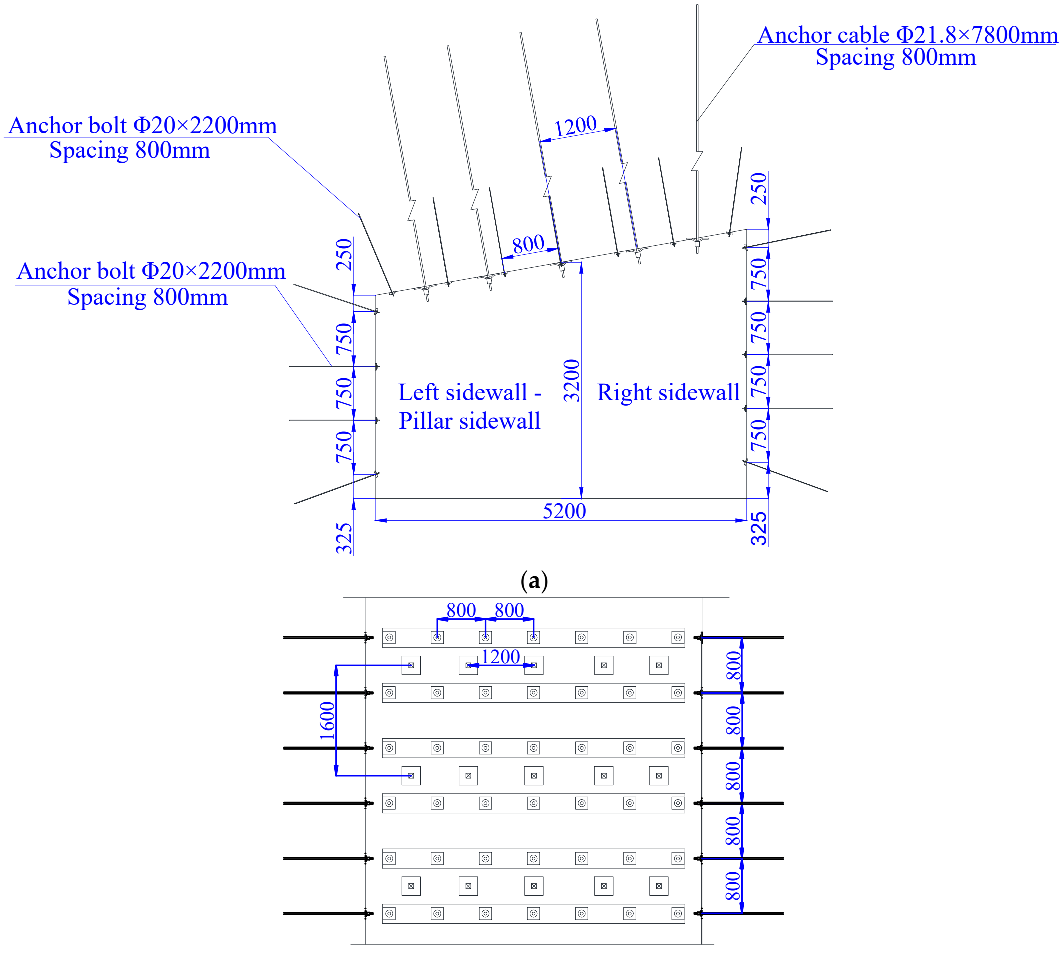
According to the numerical simulation results, the appropriate width for the coal pillar of working face 210106 in Xinji No. 2 Coal Mine is 5–7 m.

The results obtained from theoretical calculations and our numerical simulations indicated that a 5 m-wide coal pillar for goaf-side entry driving in Xinji No. 2 Coal Mine is relatively appropriate because this improves the stress state of the coal pillar and reduces the loss of coal resources.

6. Countermeasures for Control of Surrounding Rock and Field Measurements

6.1. Roadway Support Countermeasures

Haulage roadway 210106 is supported by Φ20 mm × 2200 mm high-strength threaded steel anchor bolts with steel mesh and steel strip. Four bolts are arranged on the left sidewall, and the spacing between the rows of bolts is a 750 mm × 800 mm rectangular arrangement. The right sidewall has five anchors, and the row spacing between anchors is a 750 mm × 800 mm rectangular arrangement. The roof has seven anchors, and the rows are spaced in an 800 mm × 800 mm rectangular arrangement. Five high prestressed anchor cables are arranged in the center of each row of anchor bolts on the roof. The specification of the anchor cable is Φ21.8 mm × 7800 m and the row spacing between the anchor cables is 1200 mm × 1600 mm. The roadway support parameters are shown in Figure 7. The anchor support was installed in sections.



(**a**)

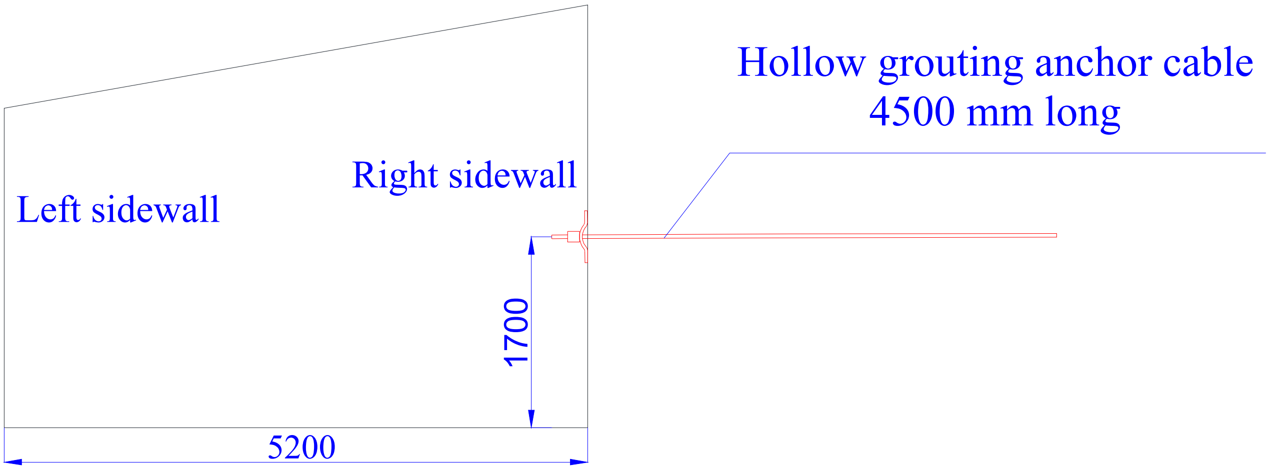
(**b**)

Figure 7. Support parameters for haulage roadway in working face 210106 (unit: mm): (**a**) section of bolt (cable) support; (**b**) top view of haulage roadway support.

6.2. Reinforcement Countermeasures for Narrow Coal Pillar

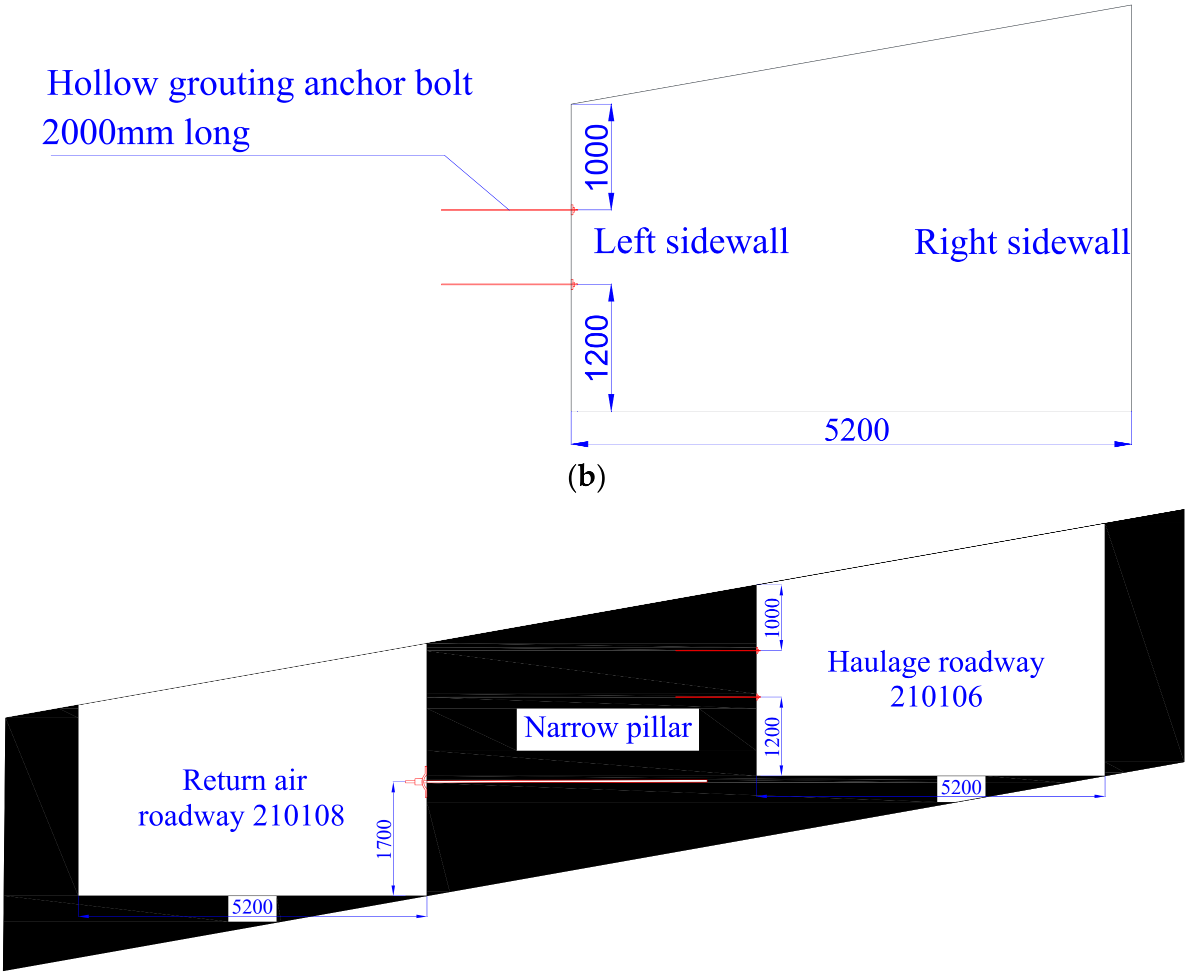
A narrow coal pillar is the weakest link in the surrounding rock structure of goaf-side entry driving. Narrow coal pillars are subject to the superposition effect produced by the mining of the upper section of the working face, the influence of excavation of the working face in this area, and also the influence of the advanced abutment pressure of the working face in this area. Therefore, the stability of the small coal pillar side is inferior to that of the solid coal side of the roadway. Serious deformation of the coal pillar will have a significant impact on the stability of the roadway roof and floor and eventually lead to the deformation and instability of the roof structure, thereby causing support failure [27–30].

Before the excavation of haulage roadway 210106, when the working face 210108 was being mined, hollow grouting anchor cable was used for grouting after spraying concrete on the right sidewall of the return air roadway 210108 to enhance the strength of the coal body in advance of the working face 100 m away. The grouting anchor cable has a diameter of 22 mm, a length of 4500 mm, and a grouting pressure of 3 MPa. The grouting anchor bolt and grouting hole layout are shown in Figure 8a. During the construction of the haulage roadway 210106, the left sidewall of the haulage roadway was sprayed with concrete and then a grouting bolt was used. The length of the grouting bolt was 2000 mm, the grouting section was 1690 mm, the anchoring section was 250 mm, and the tail thread section was 60 mm. The grouting anchor was processed by a Φ20 mm seamless steel pipe. When the grouting bolt was installed, the bolt was exposed 50 mm–100 mm, and an anchorage agent was used to seal the hole around it. The grout was ordinary Portland cement of Po.32.5 with a water-to-cement ratio of 0.75. The initial grouting pressure was 0.5 MPa, and the final pressure was 3 MPa. The lag head-on of grouting construction should not exceed 80 m. The layout of the grouting holes is shown in Figure 8b. The grouting bolt and cable for the narrow coal pillar reinforcement are arranged as shown in Figure 8c.



(**a**)

Figure 8. *Cont.*



(**b**)

(**c**)

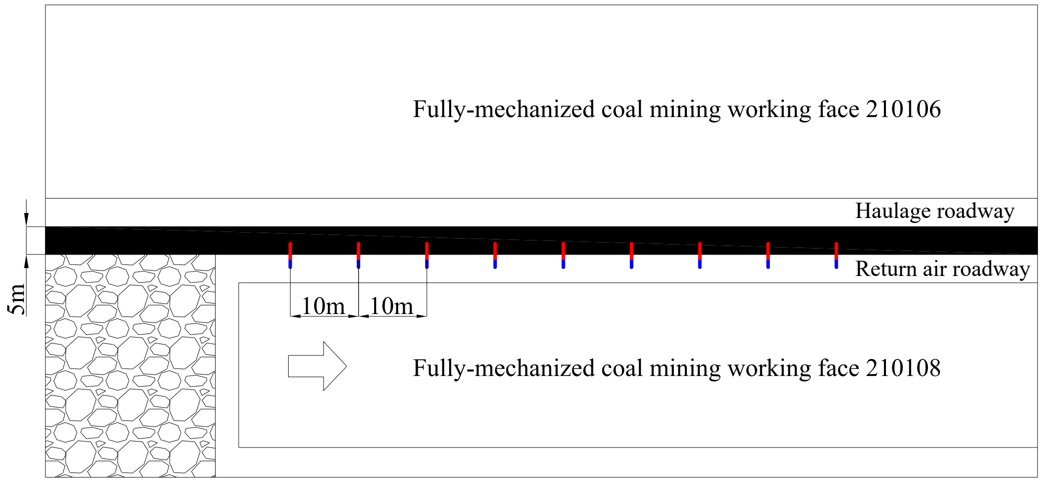
Figure 8. Diagrams showing the arrangement of grouting bolt and cable for the narrow coal pillar reinforcement: (**a**) the layout diagram of grouting anchor cable on the right side of return air roadway 210108; (**b**) grouting bolt layout on the left side of haulage roadway 210106; (**c**) section of grouting bolt and cable arrangement.

6.3. Presplitting Blasting Roof Cutting for Pressure Relief

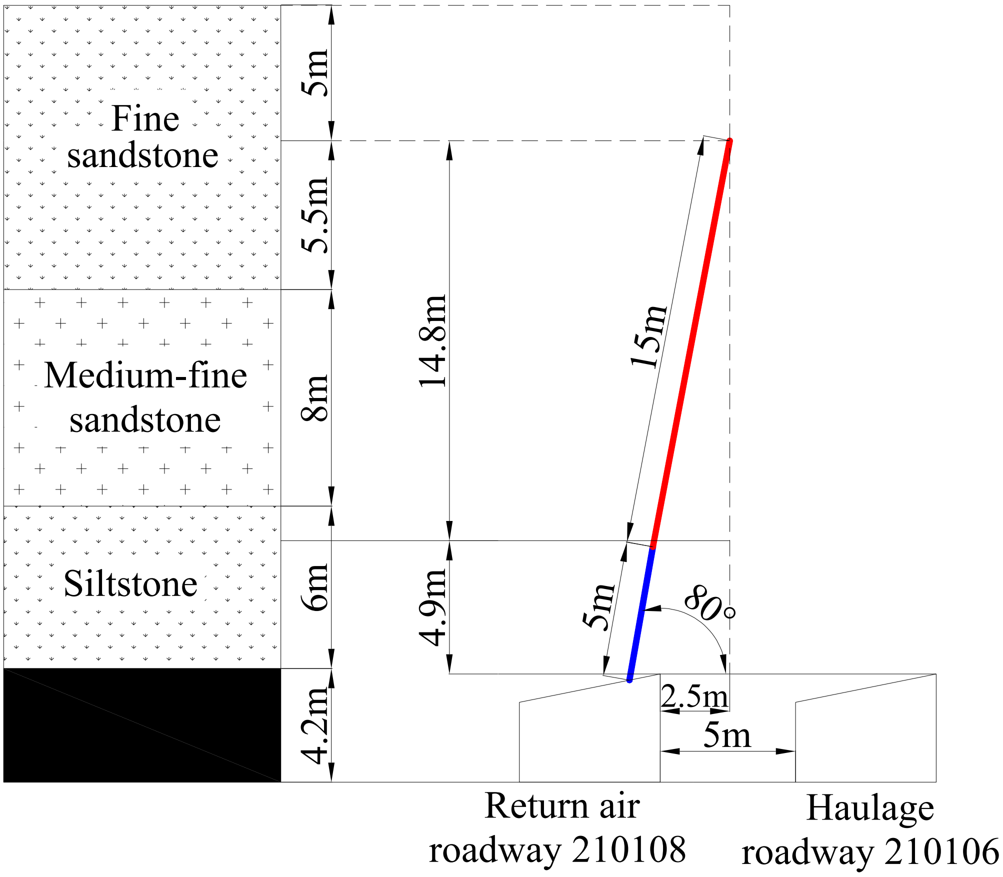
Deep borehole presplitting blasting for pressure relief [31] was carried out on the roof in the coal pillar side of the return air roadway 210108 to weaken the strength of the roof. The blasting borehole depth was 20 m, the aperture was 75 mm, the hole spacing was 10 m, the opening position was 1 m away from the coal pillar sidewall, and the inclination angle was 80°. The diameter of the mining explosive was 63 mm, the charge length was 15 m, and the sealing length was 5 m. Blasting parameters are shown in Table 3 below, and the blasting boreholes layout diagram of pressure relief is shown in Figure 9.

Table 3. The cutting roof pressure relief parameters of deep-hole presplitting blasting.

Construction Position	**Borehole Type**	**Borehole Angle (°)**	**Borehole Depth (m)**	**Borehole Diameter (mm)**	**Borehole Spacing (m)**	**Explosive Charge Length (m)**	**Diameter of Mining Explosive (mm)**	**Hole-Sealing Length (m)**
Coal pillar roof of return air roadway 210108	Presplitting blasting in roof	80	20	75	10	15	63	5



(**a**)



(**b**)

Figure 9. Layout schematic diagram of blasting boreholes of pressure relief in the roof on narrow coal pillar (unit: m): (**a**) plan of blasting boreholes layout; (**b**) section of blasting boreholes layout.

6.4. Field Measurements

The displacement variation of the roadway roof and floor and the two sidewalls was monitored using the cross-point method. The roadway surface displacement monitoring results are shown in Figure 10.

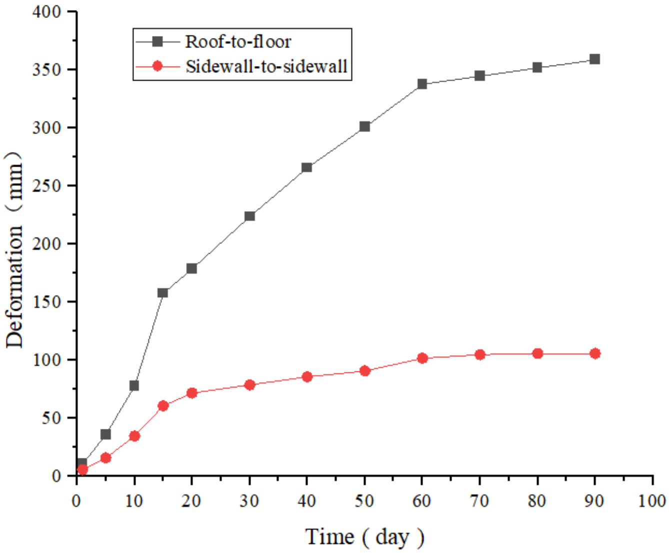


Figure 10. Roadway surface displacement monitoring results.

The measured point data curve shows that the displacement of the roadway changed rapidly in the 30 days after excavation, and the deformation of the roadway tended to become stable at around 60 days. The violent changing period of the two sidewalls of the roadway lagged behind the violent changing period of the roof and floor displacement by about 10–15 days. The displacement of the two sidewalls of haulage roadway 210106 was about 100 mm, and the displacement of the roof and floor was about 350 mm.

7. Conclusions

This paper presents a case study on pressure relief, bolt grouting reinforcement, and width optimization of narrow coal pillars for goaf-side entry driving in the deep, thick coal seam in Anhui Province, China. It provides a practical reference and guidance for other coal mines with similar geological conditions. Our conclusions are summarized as follows:

(1) The main factors influencing the deformation of rock surrounding the roadways in working face 210106 in Xinji No. 2 Coal Mine include the high ground stress, large mining height, thick sandstone in the roof, and the residual abutment pressure of the adjacent goaf;

(2) The width of the coal pillar plays a very important role in the stability of goaf-side entry driving. The results obtained from theoretical calculations, numerical simulation, and engineering practice indicated that a 5 m-wide coal pillar for goaf-side entry driving in Xinji No. 2 Coal Mine was relatively appropriate and feasible, improving the stress state of the coal pillar and reducing the loss of coal resources;

(3) The countermeasures of pressure relief of blasting roof cutting and hollow bolt and cable grouting for reinforcement of the narrow coal pillar were carried out to control the stability for goaf-side entry driving. Field measurements indicated that deformations of goaf-side entry driving in the deep, thick coal seam could be efficiently controlled. The maximum deformations of the sidewall-to-sidewall and roof-to-floor were 100 mm and 350 mm, respectively, which meet the support requirements during roadway excavation and working face mining.

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