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Research Article

Research on the Influence of Slurry Filling on the Stability of Floor Coal Pillars during Mining above the Room-and-Pillar Goaf: A Case Study

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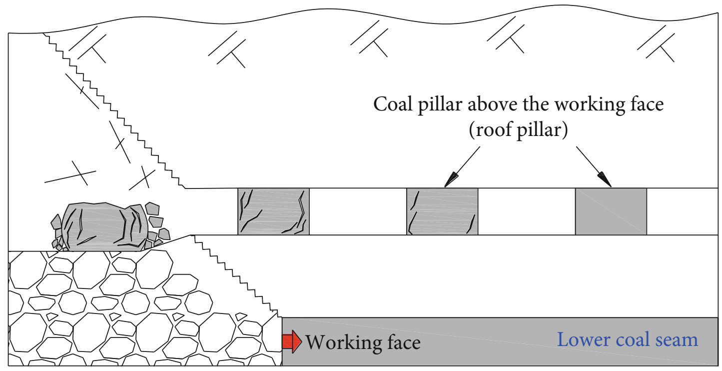
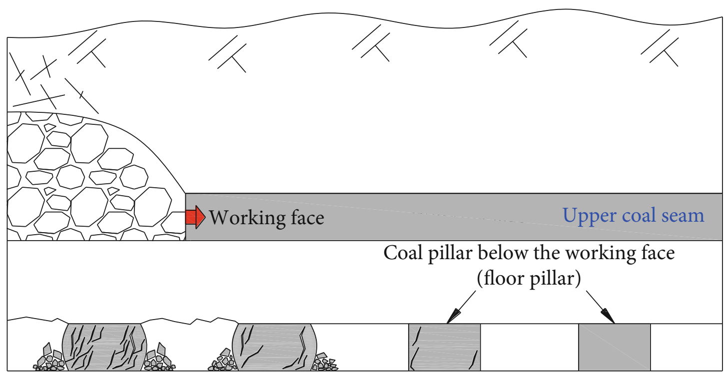
Room-and-pillar mining is a commonly used mining method in previous practice in northwest China mining area. Due to priority selection of high-quality resources, coal mines in northwest China generally have to face upward mining above goaf. Thus, the stability of a floor coal pillar influenced by mining activities plays an essential role in upward mining above goaf. The results indicated that a floor coal pillar kept stable before coal excavation in the no. 6107 working face in the Yuanbaowan coal mine; however, the plastic zone in the floor coal pillar expanded sharply and the elastic core zone reduced suddenly on the influence of abutment pressure. Finally, the floor coal pillar supported failure. Accordingly, the paper proposed a floor coal pillar reinforcing technique through a grout injection filling goaf area. As physically limited by a different-height filling body on the double sides, the plastic zone scope and horizontal displacement and loading capacity of the floor coal pillar were studied, working out that the critical height of the filling body should be about 6 m which can ensure safe mining when upward mining above goaf. Case practice indicated that the fractures induced by mining in the floor coal pillar, filling body, and floor can be restrained effectively when the filling body height is 6 m, which can ensure floor coal pillar stability and safe mining of the no. 6107 working face in the Yuanbaowan coal mine. The research can provide theoretical and technical guidance for upward mining above goaf and have a critical engineering practice value.

1. Introduction

As the largest coal production base and a well-known demonstration project of a modern mine with production capacity over 10 million tons per year in China [1], the northwestern mining area's coal production accounts for 68% of the coal production of the whole country according to 2018 statistics. In the northwestern mines, a room-and-pillar mining method was widely used in the early stage of coal mining practice [2, 3], leaving abundant coal pillars in the goaf, which puts a huge hidden threat to the safe mining of longwall working faces of adjacent coal seams. The spatial relationship between coal pillars and the longwall working faces of adjacent coal seams is mainly divided into two types: roof coal pillars and floor coal pillars, as shown in Figures 1(a) and 1(b), which indicates that the coal pillars are located above the longwall working faces and below the longwall working faces, respectively. The research results on roof coal pillars are mainly focused on the following four aspects: the occurrence mechanism of support crushing accidents in the longwall working faces under the roof coal pillars and its control measures [4–6], the stress distribution pattern of the roof coal pillars and its influence on the mining and the layout of roadways in underlying coal seams [7, 8], the calculation methods of dynamic and static loading on roof coal pillars [9–12], and the analysis and evaluation of coal pillar stability [13–16]. The research on floor coal pillars is mainly focused on their stability under the influence of the front abutment pressure to avoid the collapse of the working face and the coal and rock mass ahead caused by the failure of the floor coal pillar [17, 18]. Therefore, the key to safely mining of the longwall working face above the room-and-pillar goaf is to ensure that the floor coal pillars remain stable under the influence of mining-induced stress.



(a)



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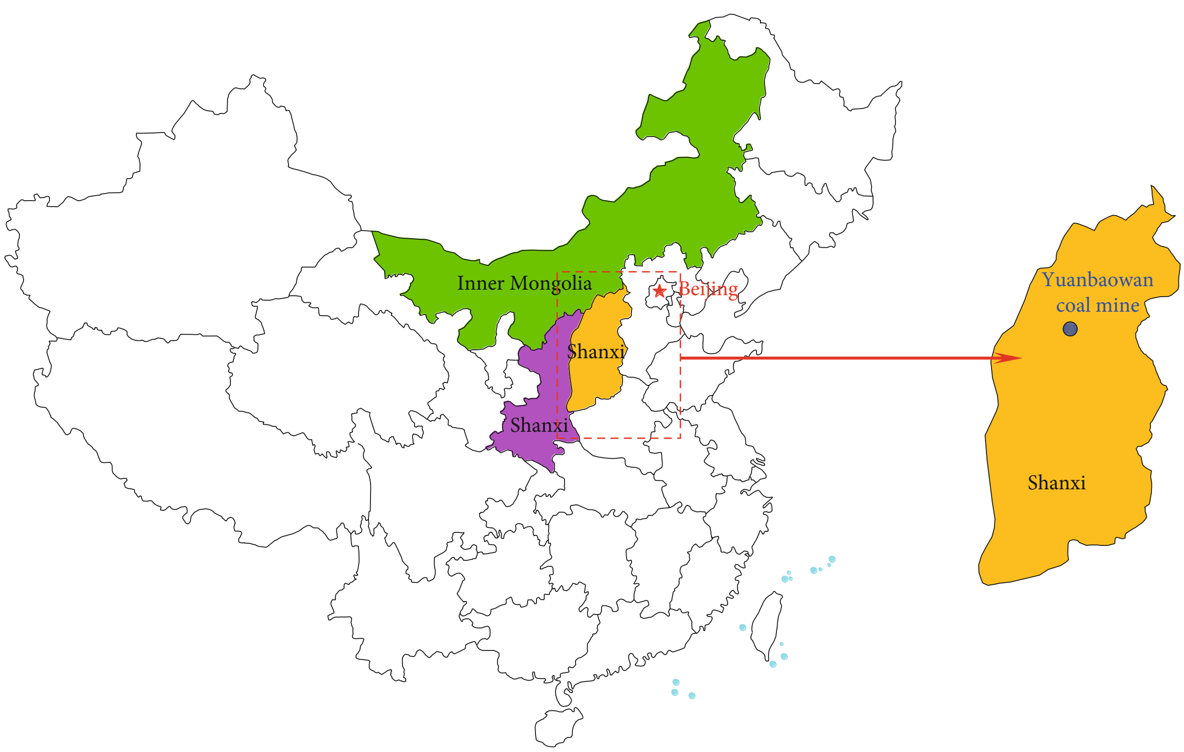
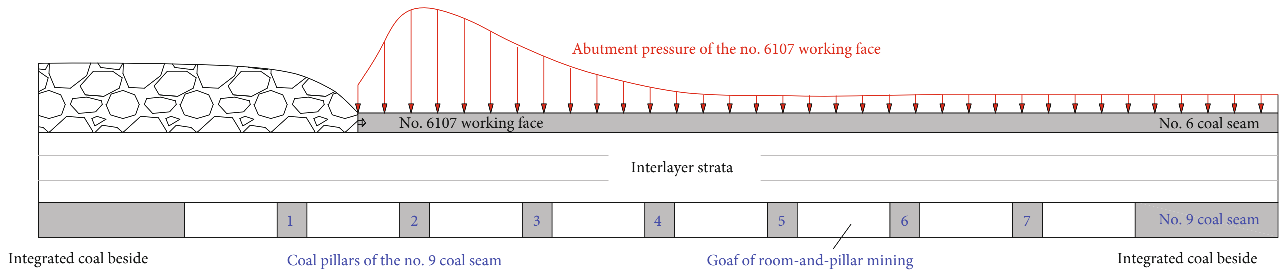


(c)

FIGURE 1: Continued.



(d)

Figure 1: The location of the Yuanbaowan coal mine and the schematic diagram of mining above the goaf: (a) roof pillar; (b) floor pillar; (c) geographic location; (d) schematic diagram of no. 6107 working face mining above the goaf.

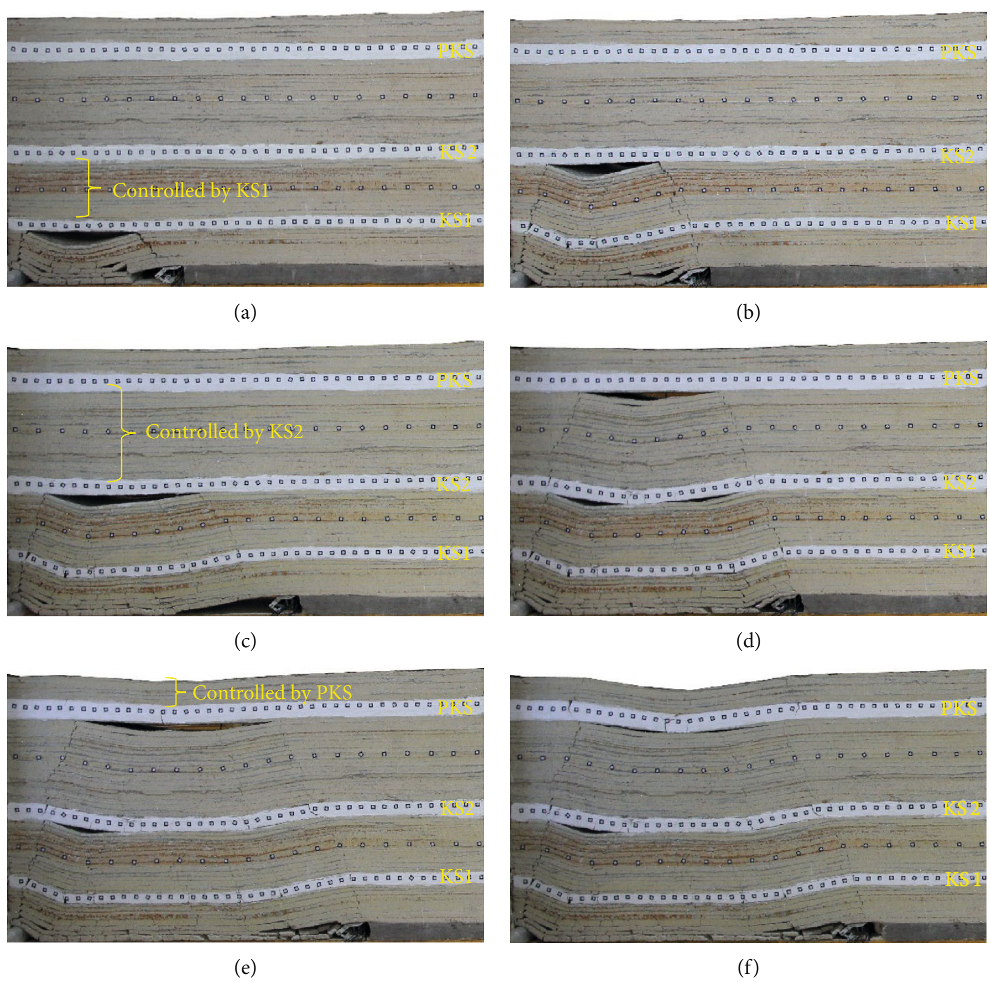


Figure 2: The control effect of the key stratum: (a) before the breakage of KS1; (b) after the breakage of KS1; (c) before the breakage of KS2; (d) after the breakage of KS2; (e) before the breakage of PKS; (f) after the breakage of PKS.

With regard to the theory and technology of safe mining of the longwall working faces above the room-and-pillar goaf, many scholars have conducted massive researches. Liu studied the influence of lithological combinations between coal seams on ascending mining [19]. Sun and Wang demonstrated the feasibility of ascending mining by adopting methods such as mining influence multiples, method of balancing the surrounding rocks, and mathematical statistical analysis [20]. Huang analyzed the stability of the floor strata of the longwall working faces above the strip goaf by using similar simulations and numerical simulations [21]. Feng et al. considered that the failure scope of the floor strata is less than the thickness of the rock interlayers as the prerequisite for safe mining of longwall working faces, and the method for determining the feasibility of ascending mining in the strip mining area was given [22–24]. Bai et al. studied the

No.	Thickness (m)	Depth (m)	Lithology	Key strata	Legend
32	38.50	38.50	Loose layer		
31	1.90	40.40	Siltstone		
30	4.00	44.40	Coarse sandstone		
29	7.60	52.00	Sandy mudstone		
28	5.80	57.80	Fine sandstone	PKS	
27	8.00	65.80	Sandy mudstone		
26	3.50	69.30	Fine sandstone		
25	0.80	70.10	Mudstone		
24	0.40	70.50	Coal		
23	2.80	73.30	Sandy mudstone		
22	1.00	74.30	Fine sandstone		
21	4.60	78.90	Sandy mudstone		
20	8.05	86.95	Siltstone	KS4	
19	4.35	91.30	Coal		
18	6.60	97.90	Mudstone		
17	1.40	99.30	Coal		
16	4.00	103.30	Sandy mudstone		
15	1.60	104.90	Fine sandstone		
14	5.50	110.40	Coarse sandstone	KS3	
13	2.00	112.40	Fine sandstone		
12	1.00	113.40	Coarse sandstone		
11	6.10	119.50	No. 4 coal		
10	2.60	122.10	Mudstone		
9	2.80	124.90	Sandy mudstone		
8	3.70	128.60	Fine sandstone		
7	7.10	135.70	Coarse sandstone	KS2	
6	3.80	139.50	No. 6 coal		
5	4.00	143.50	Mudstone		
4	3.00	146.50	Sandy mudstone		
3	5.40	151.90	Fine sandstone	KS1	
2	0.50	152.40	Mudstone		
1	8.30	160.70	No. 9 coal		

Figure 3: Location of key strata of the no. 6107 working face.

distribution law of the mining-induced stress on the middle coal seam when above and below the working face lie the room-and-pillar mining goafs by applying a numerical simulation method [25, 26]. By reviewing the existing literature, it can be found that the research results above are mainly focused on the feasibility evaluation of mining above goaf and that the failure scope of the floor rock is less than the thickness of the rock interlayers, which has been considered as the standard for mining above goaf. However, the mining damage scope of the floor strata is significantly greater than the thickness of the interlayer strata when mining in extremely close coal seams, and few studies have given safe mining techniques under such conditions. Therefore, the safe mining technology of the upper coal seam needs further study in the case of extremely close-distance coal seams.

Based on the mining conditions of the Yuanbaowan coal mine in Shanxi Province, this article proposes a new engineering technology to safely mine the upper coal seams by strengthening the bearing capacity of the floor coal pillars with the method of backfilling the room-and-pillar mining

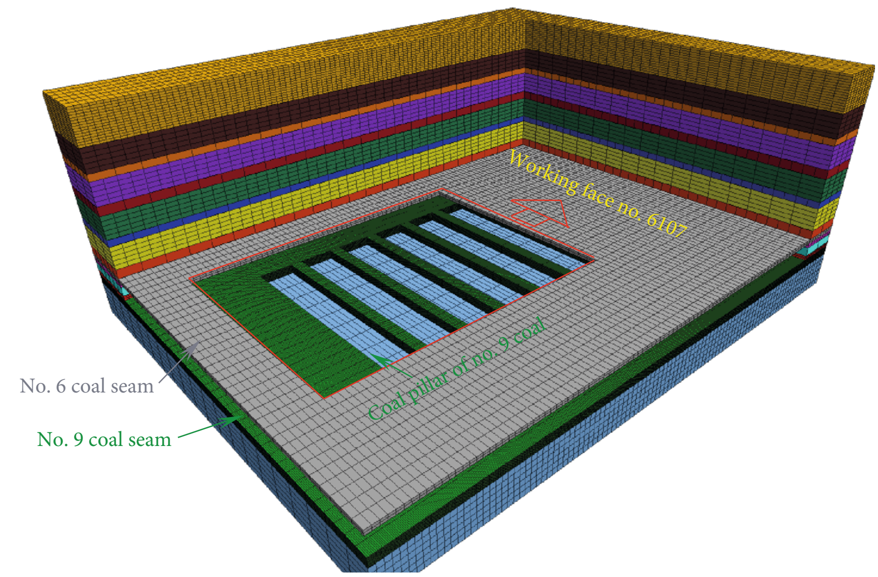
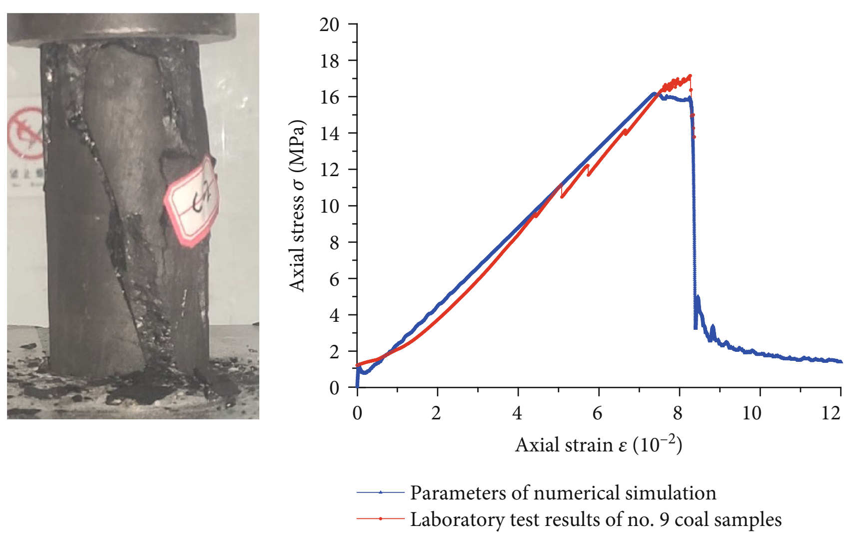


Figure 4: Schematic diagram of no. 6107 working face mining above the room-and-pillar goaf.



(a) Coal sample

(b) Stress-strain curve

Figure 5: Calibration result of the coal seam simulation parameter.

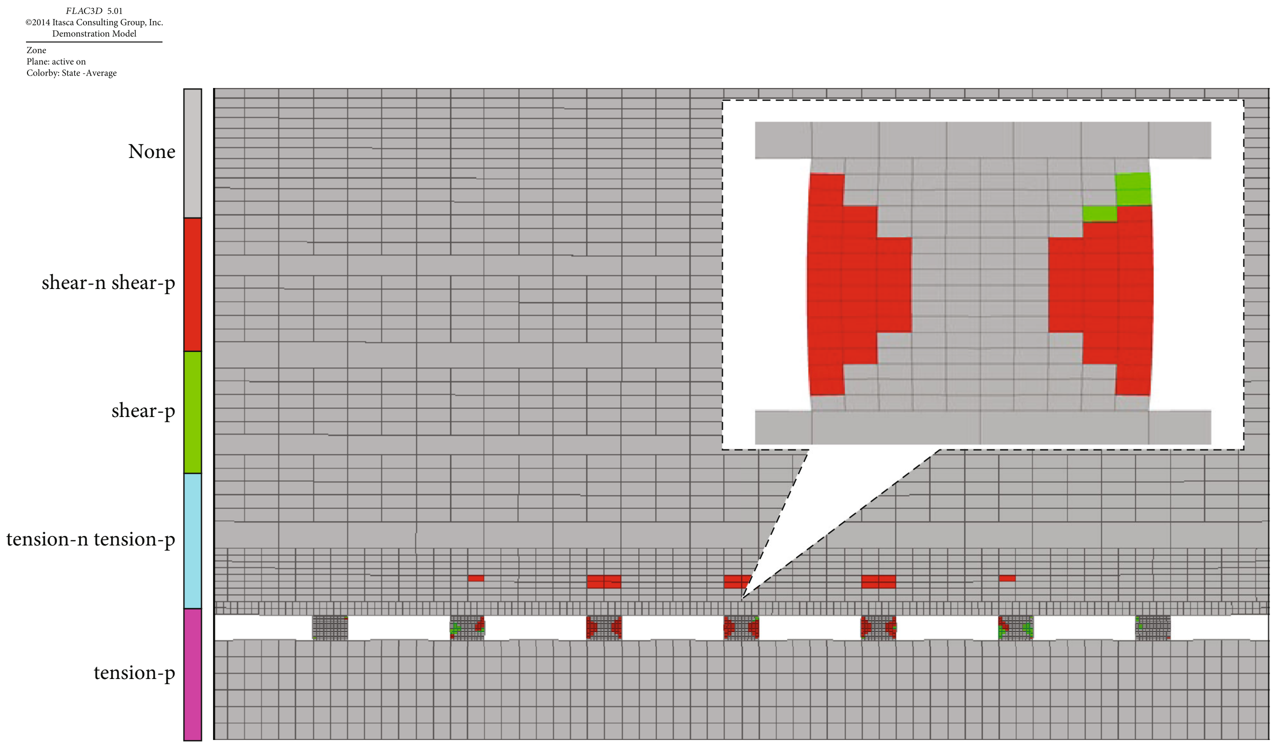
Table 1: Parameters in FLAC3D numerical simulation.

Layers	Bulk modulus b (Pa)	Shear modulus s (Pa)	Cohesion c (MPa)	Internal friction angle f (°)	Tensile strength t (MPa)
Soft rock	$5.00E+09$	$3.40E+09$	$3.40E+06$	24	$1.80E+06$
Coal seam	$4.00E+09$	$3.00E+09$	$2.20E+06$	18	$1.50E+06$
Key strata	$7.50E+09$	$4.50E+09$	$4.30E+06$	32	$2.50E+06$

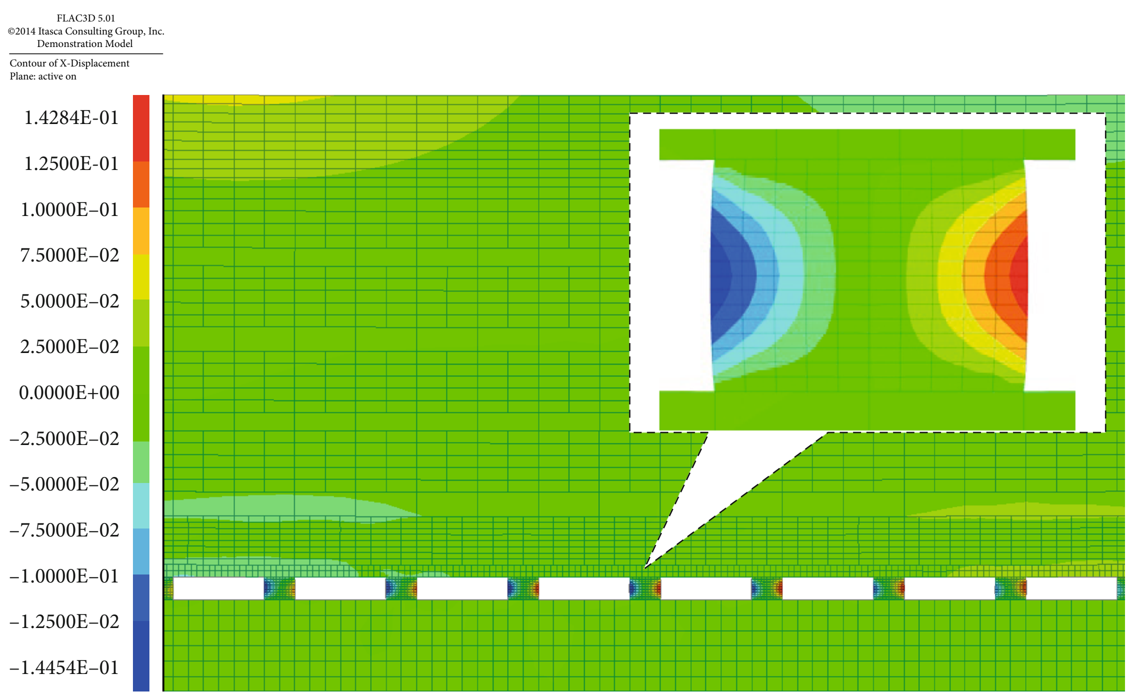
goaf. The filling body formed by the concretion of the cement slurry has a lateral clamping effect on the floor coal pillars. And the effects of difference in filling bodies' heights on the suppression of the expansion of the floor coal pillars' plastic area and on strengthening the bearing capacity of the floor coal pillars are also different. Accordingly, the critical height of filling bodies to ensure the stability of the floor coal pillars is given in this paper. The research results can provide important theoretical and engineering technical support for the safe mining of longwall working faces above the goaf.

2. Geological Conditions

2.1. General Situation of the Working Face. The Yuanbaowan coal mine is located in Shuozhou City, Shanxi Province, China, of which the no. 6107 working face is the first coal

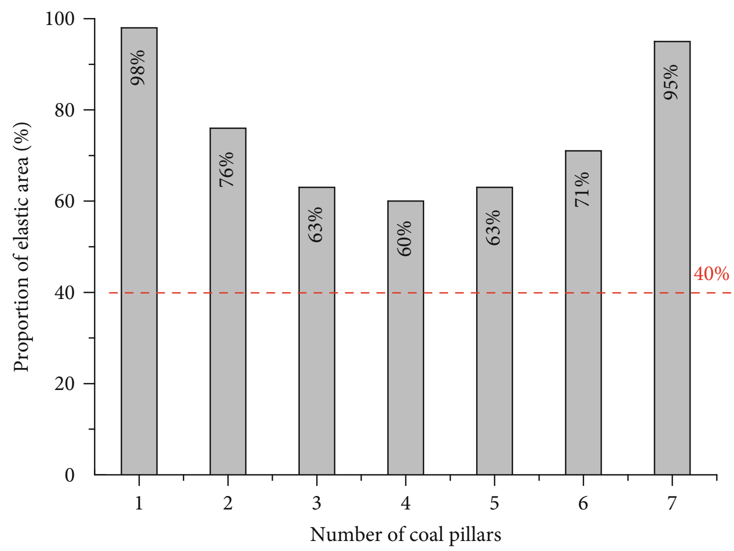


(a)



(b)

Figure 6: Continued.



(c)

Figure 6: Initial stability of coal pillars below the no. 6107 working face before mining: (a) elastic-plastic regional distribution of the no. 4 coal pillar; (b) heave of the left and right side of the no. 4 coal pillar; (c) proportion of elastic core areas of each coal pillar.

mining face in the first panel. The no. 6107 working face is deployed in the no. 6 coal seam. The no. 6 coal seam dip angle is 0°–6°, with an average mining height of 3.6 m. The width of the no. 6107 working face is 240 m, with an accumulated advancement distance of about 600 m. Below the no. 6 coal seam lies the no. 9 coal seam, with an average thickness of about 8.0 m. As of May 2005, the no. 9 coal seam had been fully mined out by the room-and-pillar mining method. In the no. 9 coal seam appears the room-and-pillar mining goaf when the no. 6107 working face advances between 200 m and 400 m. Affected by both the early mining design and planning and the unauthorized cross-border mining, mining above the room-and-pillar goaf is not a specific case for the Yuanbaowan coal mine but a relatively common type of mining conditions for shallow coal seams in northwestern China. Achieving safe mining of the longwall working faces above the room-and-pillar goafs is a major technical problem remaining urgently to be solved not only in the Yuanbaowan coal mine but also in most mines in northwestern China.

For the room-and-pillar goafs below the no. 6107 working face in the Yuanbaowan coal mine, the width of the coal pillar is about 10-12 m and the space between pillars is about 25-30 m. The geographical location of the Yuanbaowan coal mine and the mining situation of the no. 6107 working face are shown in Figures 1(c) and 1(d).

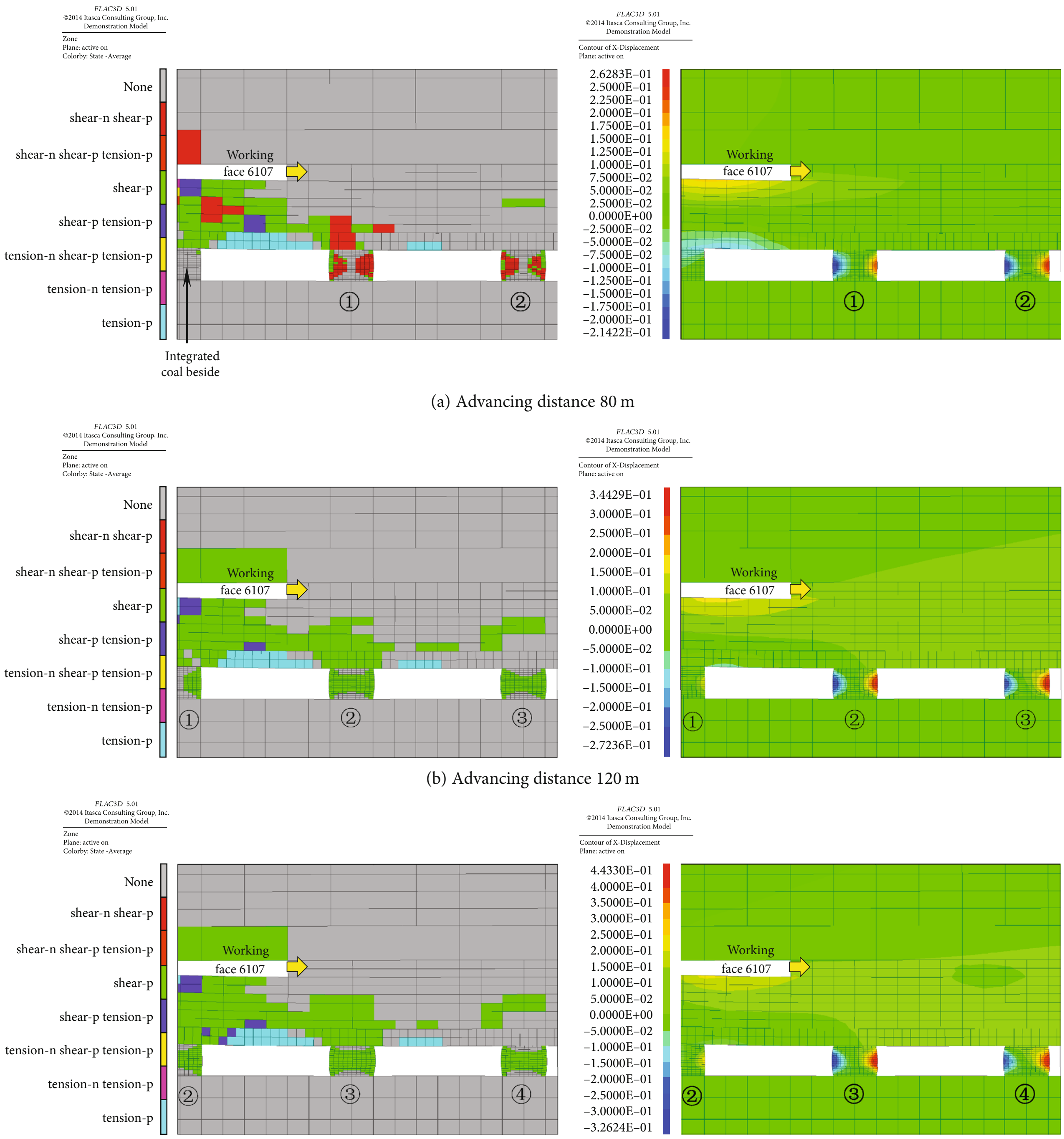
2.2. Columnar Overburden Stratum of the Working Face

2.2.1. Key Stratum Theory. The stratification of the coal system strata leads to differences in the motions of each stratum; In particular, thick and hard strata control these motions, while thin and soft strata act as loads. Based on the recognition of these facts, the Chinese scientist Minggao Qian proposed the “key stratum theory in ground control” in 1990. The theory treats the stratum that controls some or all of the strata above it up to the ground surface as the key stratum. This implies that deformation or breakage of the key stratum would simultaneously cause deformation or breakage of the strata under its control. One or more key strata exist in the overlying strata of a coal mine. Because the topmost key stratum controls the stratum movement up to the ground surface, it is referred to as the primary key stratum (PKS), while all other key strata are referred to as a subkey stratum (SKS). This “controlling effect” of the key strata is illustrated in Figure 2. The key stratum theory provides a sound foundation on understanding the progressive caving behavior of strata. The strata behavior is primarily controlled by the breakage and movement of the KS. The theory has been widely used and demonstrated in the mining industry in China [27–32]. This study is also preceded on the basis of this theory.

2.2.2. Key Stratum of the No. 6107 Working Face. According to the key stratum theory of stratum control, the key strata in the overlying strata of the no. 9 coal seam are identified with the help of key stratum identification software. The results are shown in Figure 3. It can be seen that there are altogether 5 key strata in the overlying strata of the no. 9 coal seam. From bottom to top, they are fine sandstone with a burial depth of 151.90 m and a thickness of 5.4 m, coarse sandstone with a burial depth of 136.10 m and a thickness of 7.5 m, coarse sandstone with a burial depth of 110.40 m and a thickness of 5.5 m, siltstone with a burial depth of 86.95 m and a thickness of 8.05 m, and fine sandstone with a burial depth of 57.80 m and a thickness of 5.8 m, respectively. The distinguishing method of the key stratum in overburden can be seen in Reference 29, which is limited to space and will not be repeated here.

3. Numerical Simulation

3.1. Modelling and Mining Scheme. The FLAC3D numerical calculation model is established, as shown in Figure 4,

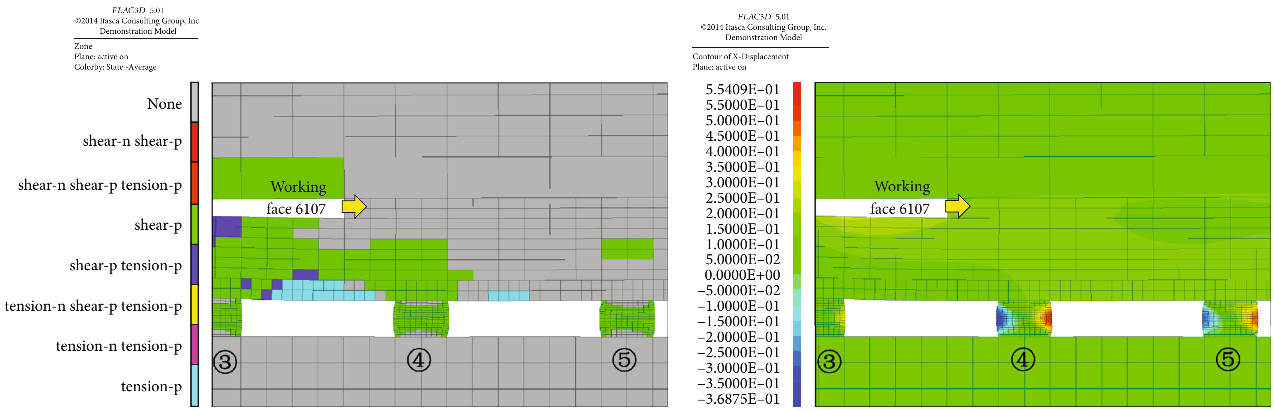


(a) Advancing distance 80 m

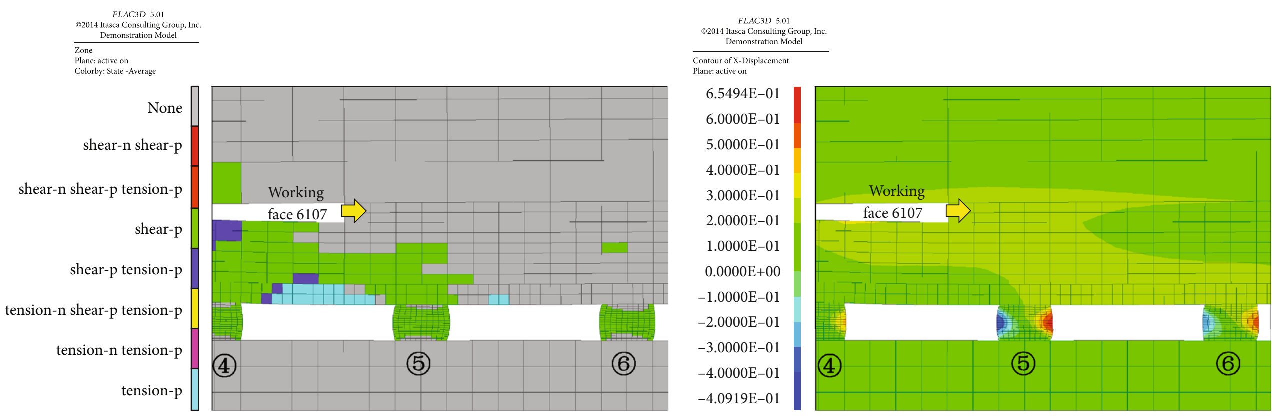
(b) Advancing distance 120 m

(c) Advancing distance 160 m

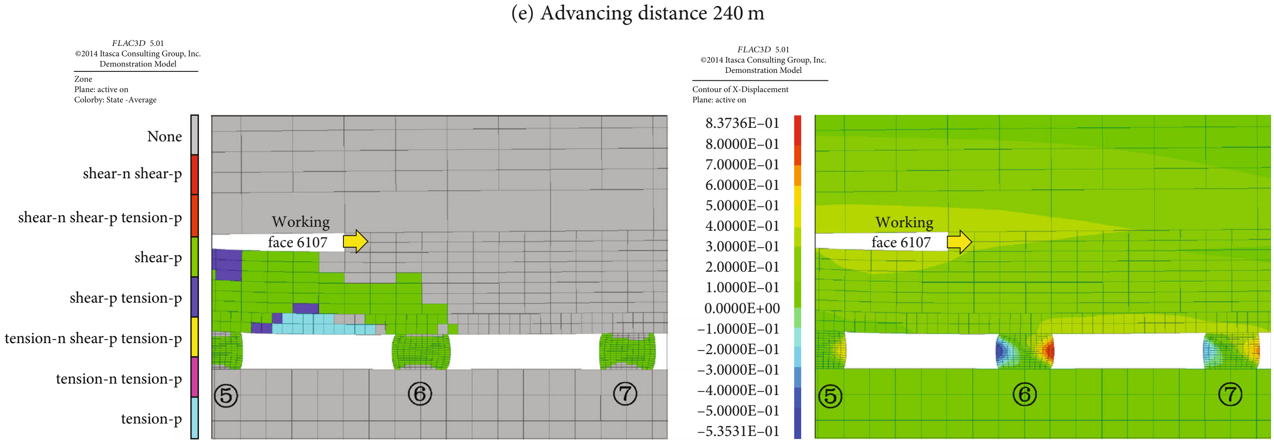
Figure 7: Continued.



(d) Advancing distance 200 m

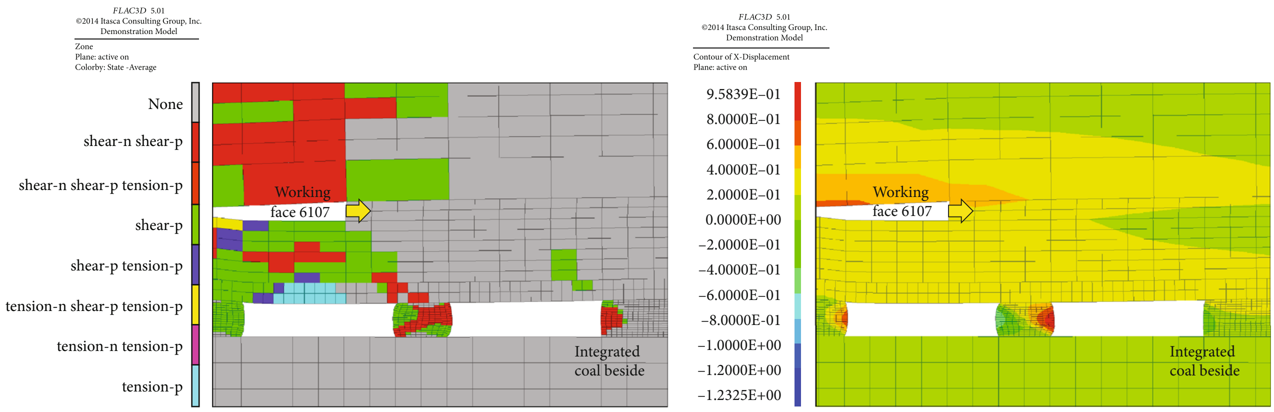


(e) Advancing distance 240 m

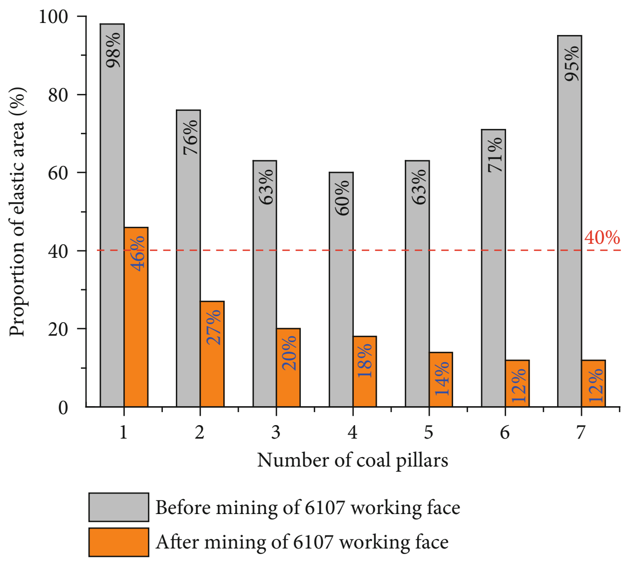


(f) Advancing distance 280 m

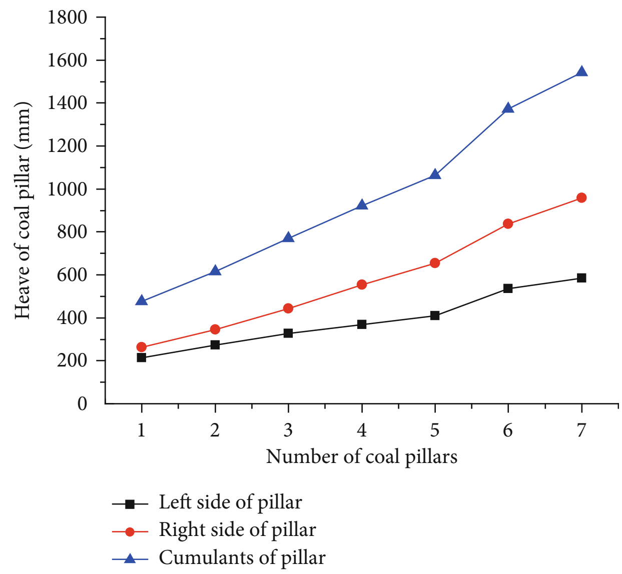
Figure 7: Continued.



(g) Advancing distance 320 m



(h) Proportion of the elastic core area of each coal pillar



(i) Heave of the left and right side of the coal pillar

Figure 7: Evolution law of the elastic-plastic property and the amount heave of the left and right side of the coal pillar under different advancing distances of the no. 6107 working face.

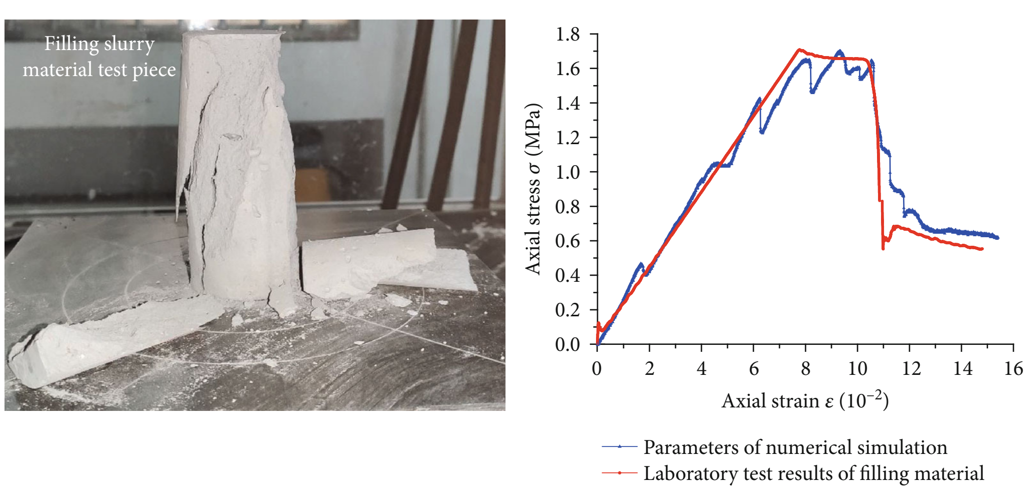
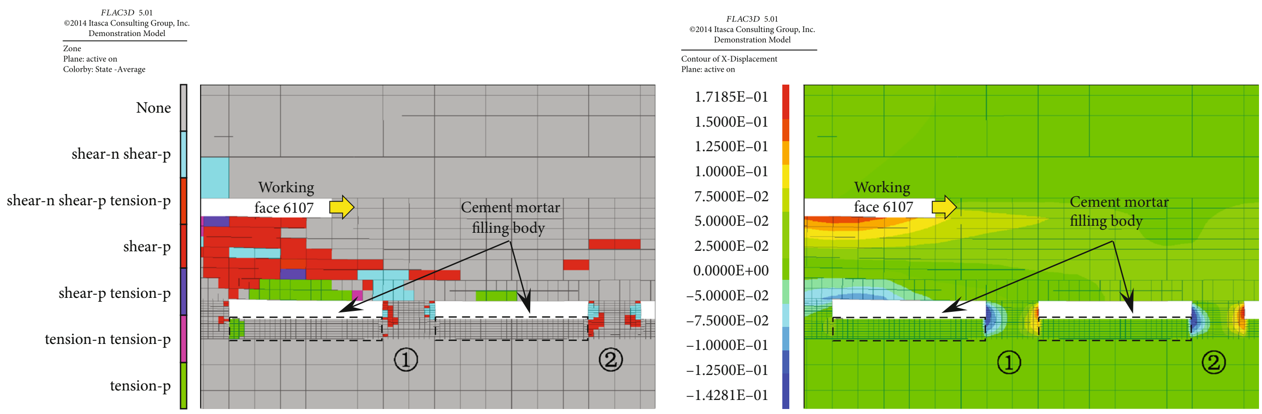
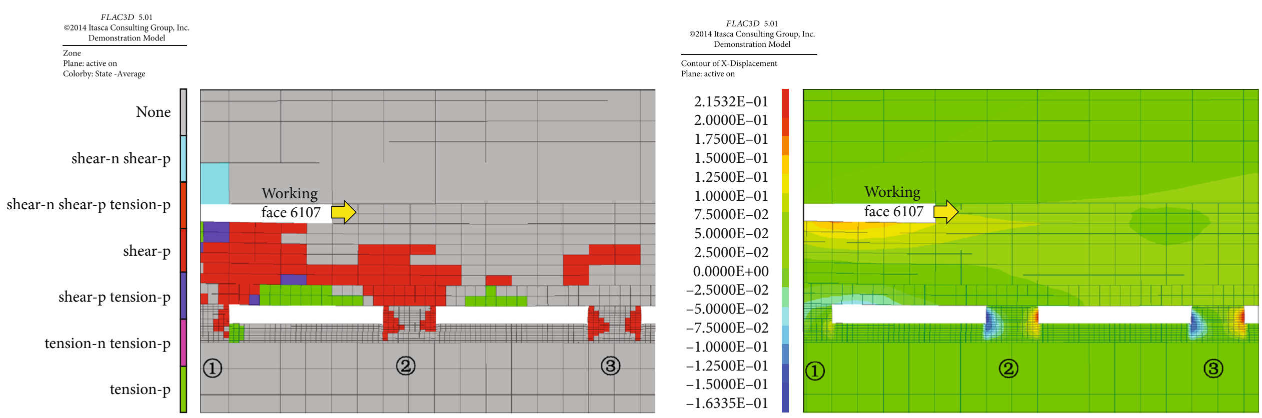


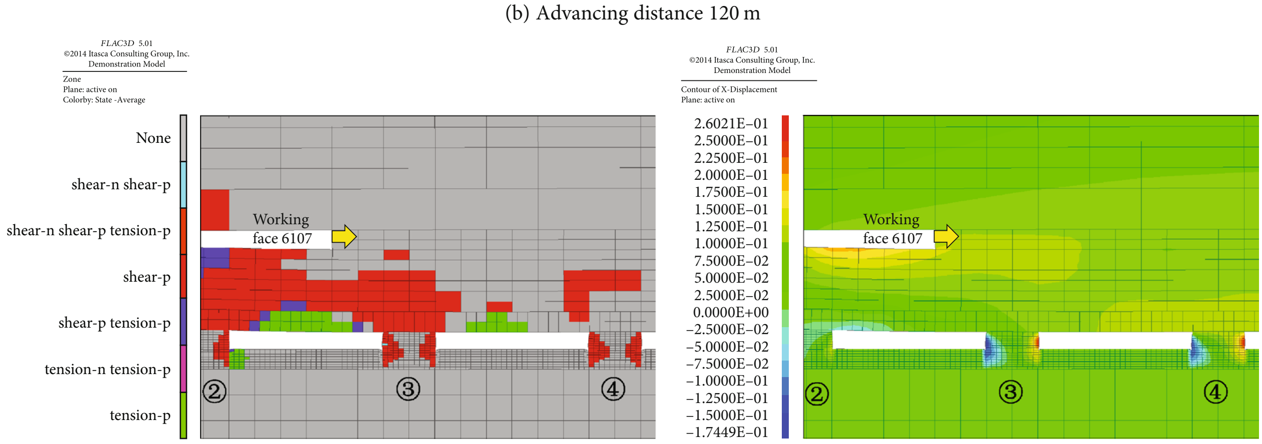
Figure 8: Calibration result of the filling material simulation parameter.



(a) Advancing distance 80 m

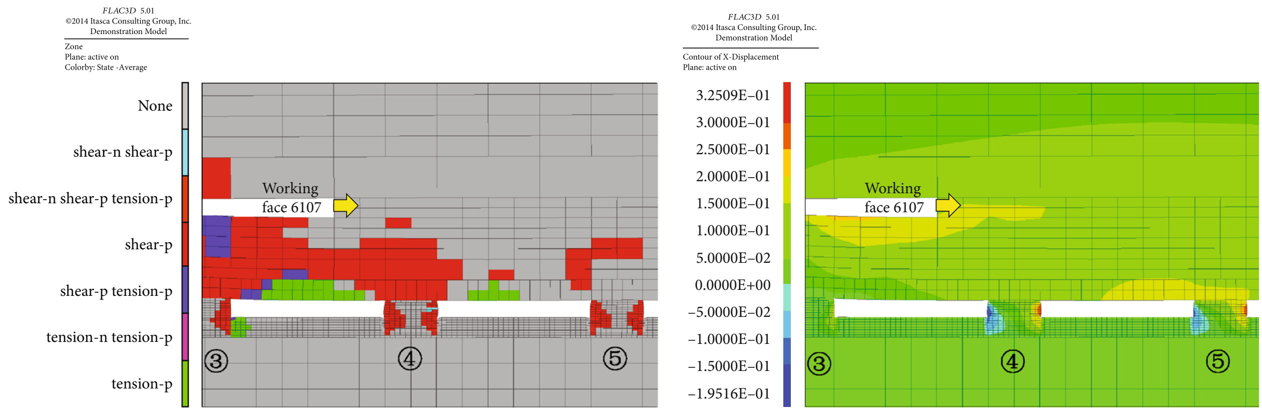


(b) Advancing distance 120 m

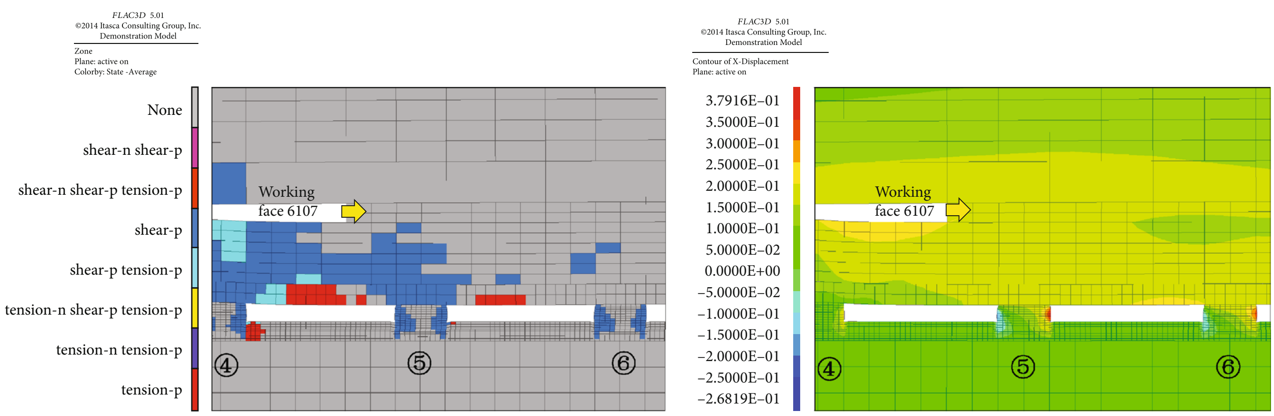


(c) Advancing distance 160 m

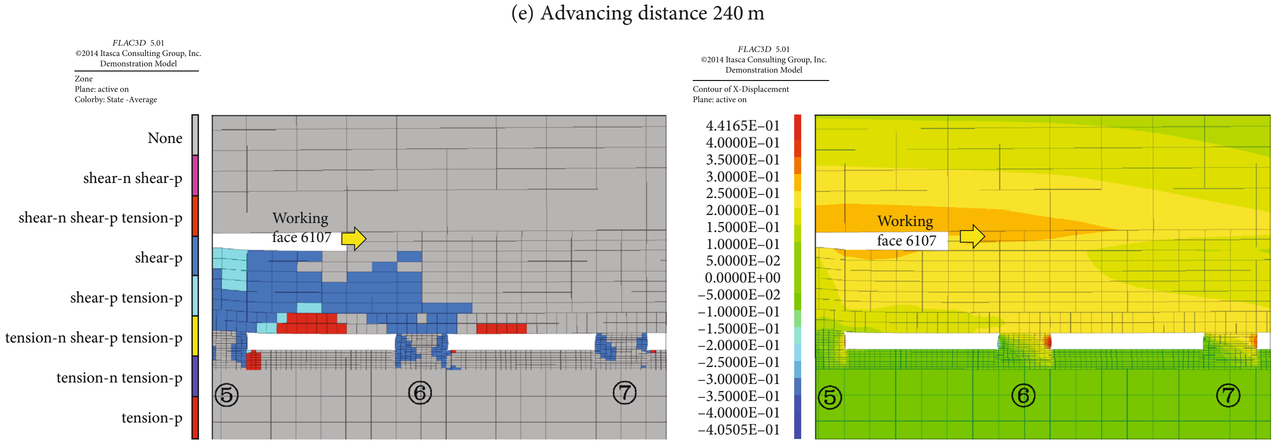
Figure 9: Continued.



(d) Advancing distance 200 m

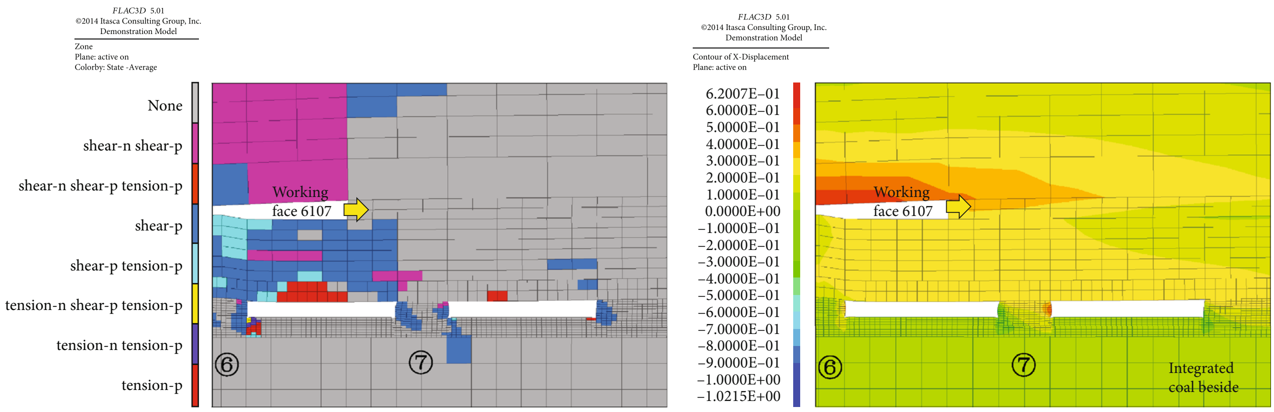


(e) Advancing distance 240 m



(f) Advancing distance 280 m

Figure 9: Continued.



(g) Advancing distance 320 m

Figure 9: The elastoplastic expansion and the amount of the horizontal bulge of each coal pillar with a filling body height of 4 m.

according to identification results of the key strata in the overlying strata. And the KS1, KS2, KS3, KS4, and PKS in the figure refer to the key strata of the overlying strata of the no. 9 coal seam.

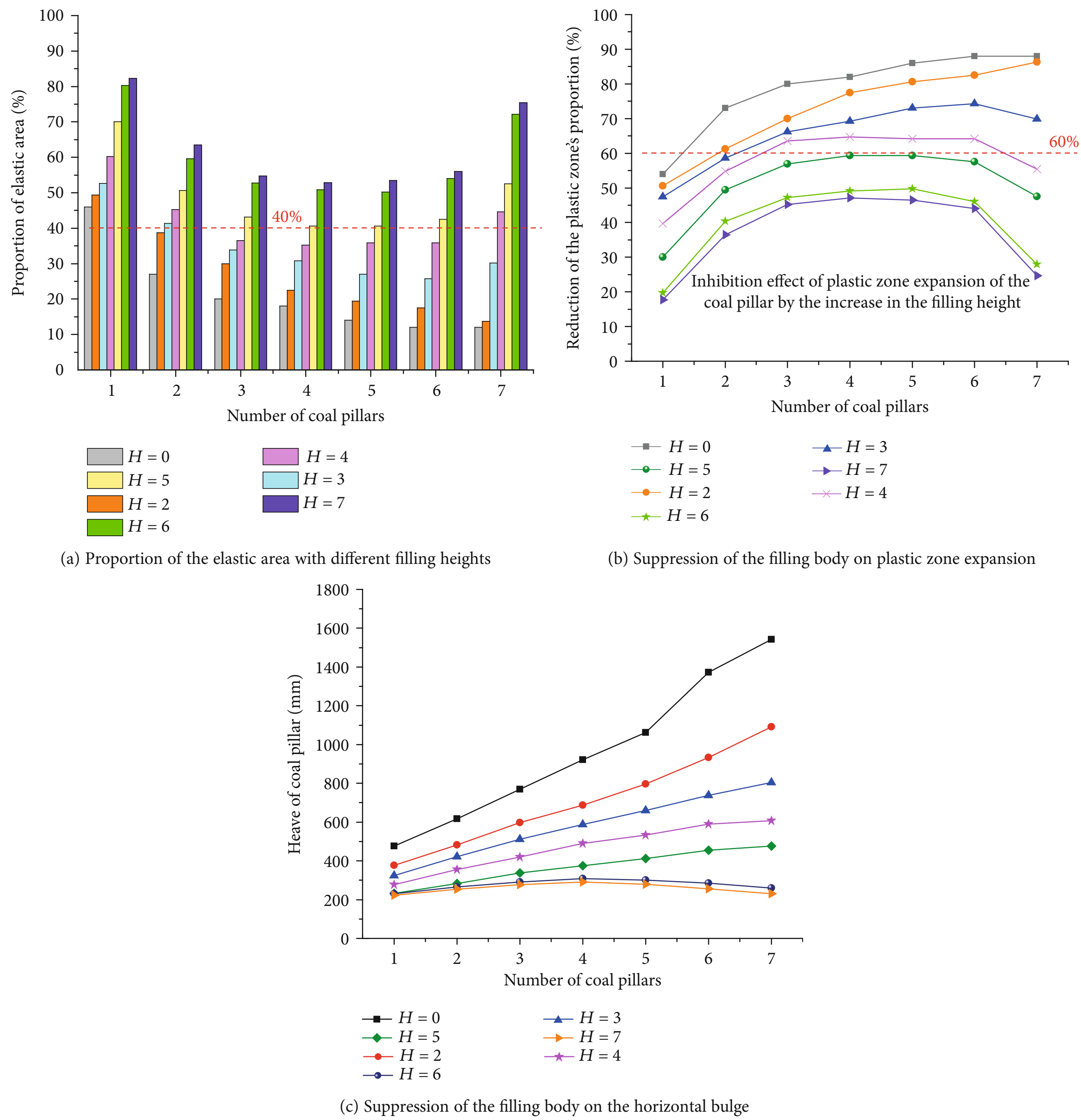
The simulation research work is carried out in the following three steps. First, room-and-pillar goaf is formed in the no. 9 coal seam in the model under the premise of the balance of the geostatic stress field. Secondly, the stability of the floor coal pillars with the condition that its goaf is unfilled in the no. 9 coal seam is investigated under the influence of mining of the no. 6107 working face. Finally, the stability of the floor coal pillar, during the advancement of the no. 6107 working face, was studied with the condition that room-and-pillar goaf has been filled in the no. 9 coal seam. Based on this, the effect rules of difference in filling bodies' heights on the suppression of the expansion of the floor coal pillars' plastic area and on strengthening the bearing capacity of the floor coal pillars were revealed. Accordingly, the critical height of filling bodies for the no. 9 room-and-pillar goaf is obtained to ensure safe mining in view of the geological conditions of the no. 6107 working face.

3.2. Calibration of Coal Seam Simulation Parameters. Correctly selecting material parameters in numerical simulation is not only a key prerequisite for accurately investigating the stability of the coal pillars below the no. 6107 working face but also the basis for ensuring that the numerical simulation results are consistent with the actual situation. Accordingly, the no. 9 coal seam is sampled and the physical and mechanical parameters are obtained through laboratory tests. In the uniaxial compression experiment, according to the international rock mechanics test experiment specification, a cylindrical specimen with a geometric size of φ50mm × 100 mm was selected, and the loading speed of the electrohydraulic servo universal testing machine was 0.02 mm/s ~0.05 mm/s. And then, uniaxial compression curve experiments are performed in FLAC3D, and the strain softening model is applied to obtain simulated parameters relatively consistent with the laboratory test results. As shown in Figure 5, the red curve is the uniaxial compression curve (obtained from the laboratory tests) of the coal sample of the no. 9 coal seam and the blue curve is the numerical simulation result of FLAC3D, and the simulation parameters are shown in Table 1. There is much consistency in the elasticity modulus and peak strength of both. It can be seen that the simulated parameters of the blue curve can be used as the parameters of the no. 9 coal seam, which can accurately reflect the stress evolution, elastic and plastic expansion, and failure modes of the coal pillars in the no. 9 coal seam under the influence of mining-induced stress of the no. 6107 working face.

4. Stability of Floor Pillars

4.1. Stability of Floor Pillars before the Mining of the No. 6107 Working Face. The vertical stress, horizontal displacement, and elastic-plastic area of the coal pillar in the goaf of the no. 9 coal seam before mining of the no. 6107 working face are shown in Figures 6(a)–6(c), respectively. It can be seen that the no. 4 coal pillar has the largest horizontal side heaves among all the coal pillars, and its value is 145 mm. The elastic core area of each coal pillar accounts for 98%, 76%, 63%, 60%, 63%, 71%, and 95% of the total volume of the coal pillar, as shown in Figure 6(c). It is worth noting that both the proportion of the elastic core area of coal pillars in the room-and-pillar goaf in northwestern China and its relationship with the stability of the coal pillars have been carefully studied in literature [33]. It has been pointed out that when the elastic core area of the coal pillars accounts for 40% of the total volume, the coal pillar is considered to be in a stable state. In order to ensure the safety mining of the no. 6107 working face to the greatest extent, the identification standard, where the elastic core area makes up 40% of the total volume of coal pillars, for the stability of the coal pillar has been set. It can be known that the coal pillar of the no. 9 coal seam was in a stable state before mining of the no. 6107 working face.

4.2. Stability of Floor Pillars during the Mining of the No. 6107 Working Face. During the mining of the no. 6107 working face, both the horizontal side heave and the plastic area of the coal pillar further expanded due to the influence of the abutment pressure, and the proportion of the elastic core area of the coal pillar further reduced. According to the existing research results, it is generally considered that the peak value



(a) Proportion of the elastic area with different filling heights

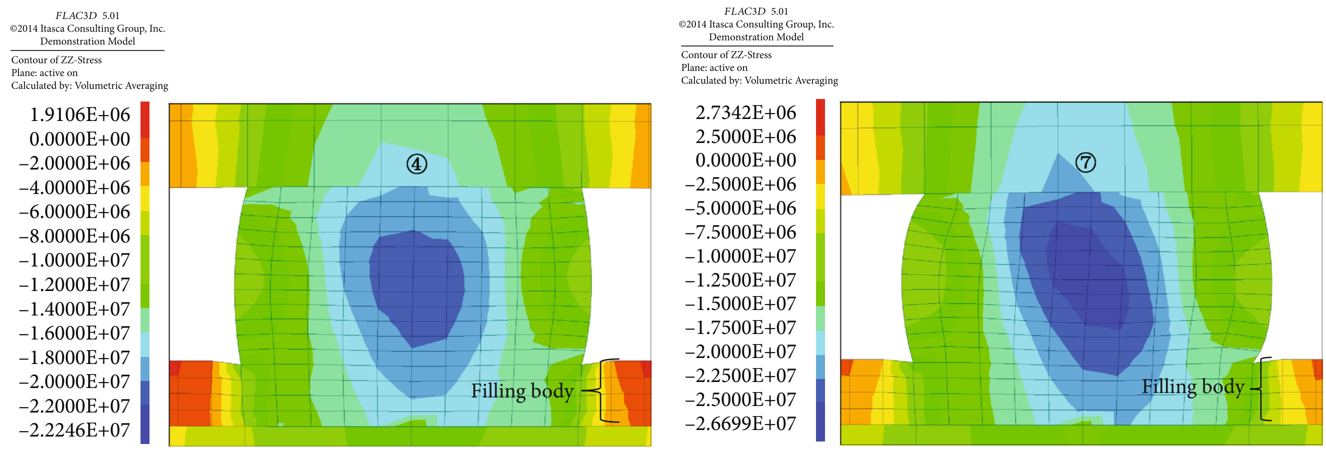
(b) Suppression of the filling body on plastic zone expansion

(c) Suppression of the filling body on the horizontal bulge

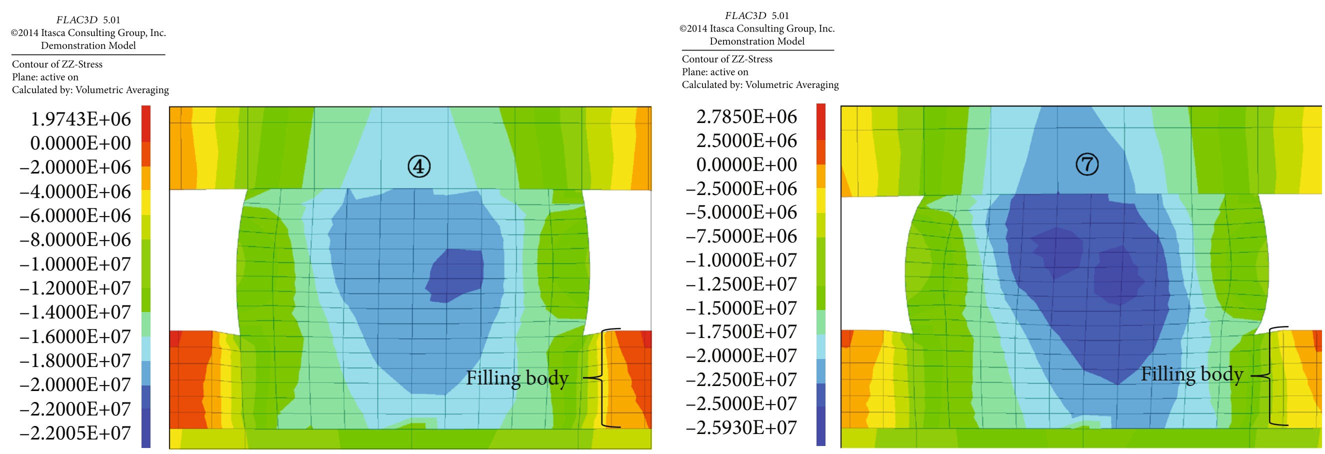
Figure 10: Suppressing effect of different filling body heights on the expansion of the plastic zone and the amount of the horizontal bulge of each coal pillar.

of front abutment pressure is located 0-10 m in front of the coal mining working face [34–36]. Therefore, the floor coal pillar is most likely to be destroyed when it is at the position of the peak value of front abutment pressure. The proportion of elastic/plastic areas, horizontal side heaves, and bearing capacity of each coal pillar are studied in this case. The evolutionary process of both elastic-plastic area expansion and the horizontal side heave of each floor coal pillar is shown in Figures 7(a)–7(g) during the advancing of the no. 6107 working face.

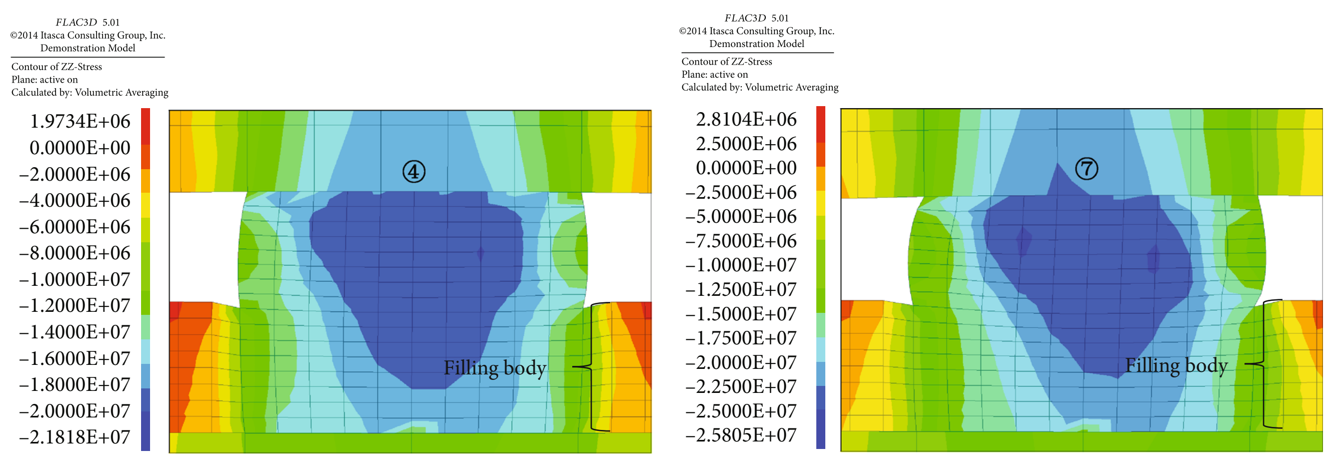
It can be seen from Figure 7 that under the influence of the abutment pressure of the no. 6107 working face, the proportions of the elastic area of each floor pillar have been reduced to 46%, 27%, 20%, 18%, 14%, 12%, and 12%, respectively. And the volume of the horizontal side heave of each floor coal pillar increases from 220 mm, 241 mm, 268 mm, 275 mm, 271 mm, 247 mm, and 220 mm to 476 mm, 616 mm, 769 mm, 922 mm, 1063 mm, 1372 mm, and 1543 mm, respectively. The dramatic reduction of the elastic core area will definitely cause the instability of the coal



(a) Filling body heights 2 m

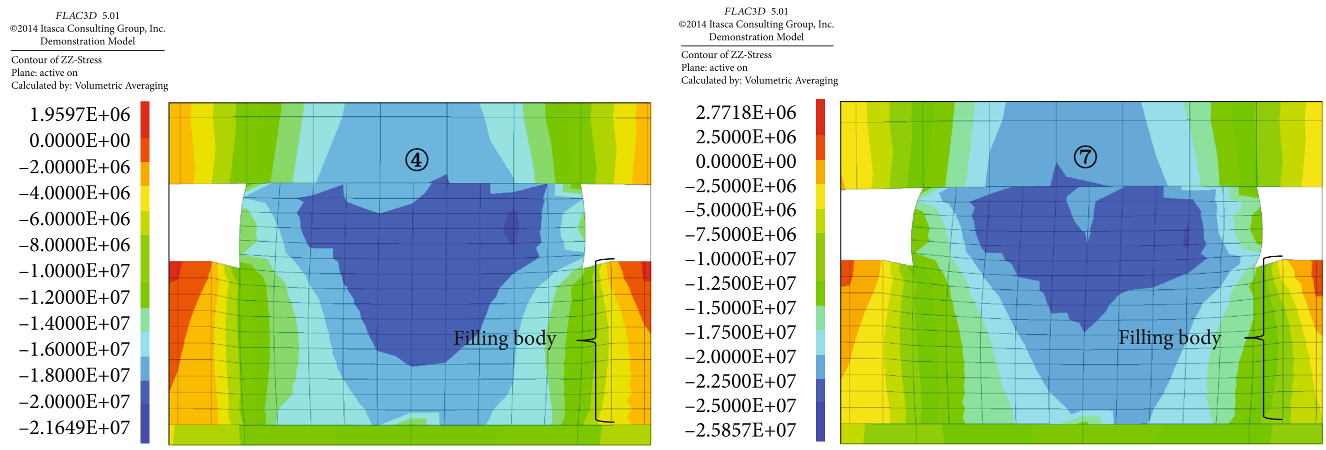


(b) Filling body heights 3 m

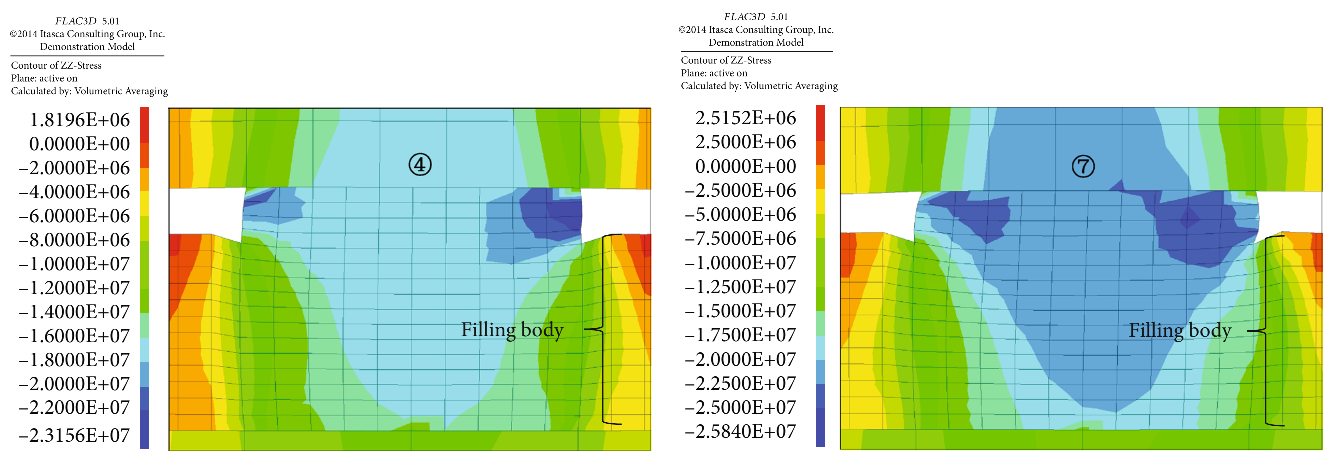


(c) Filling body heights 4 m

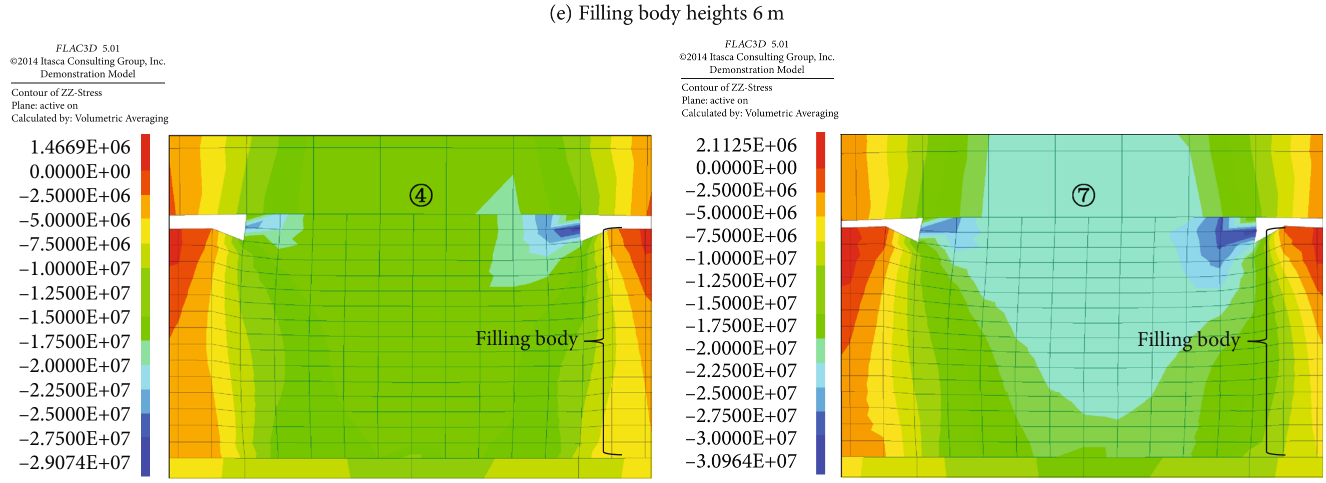
Figure 11: Continued.



(d) Filling body heights 5 m



(e) Filling body heights 6 m

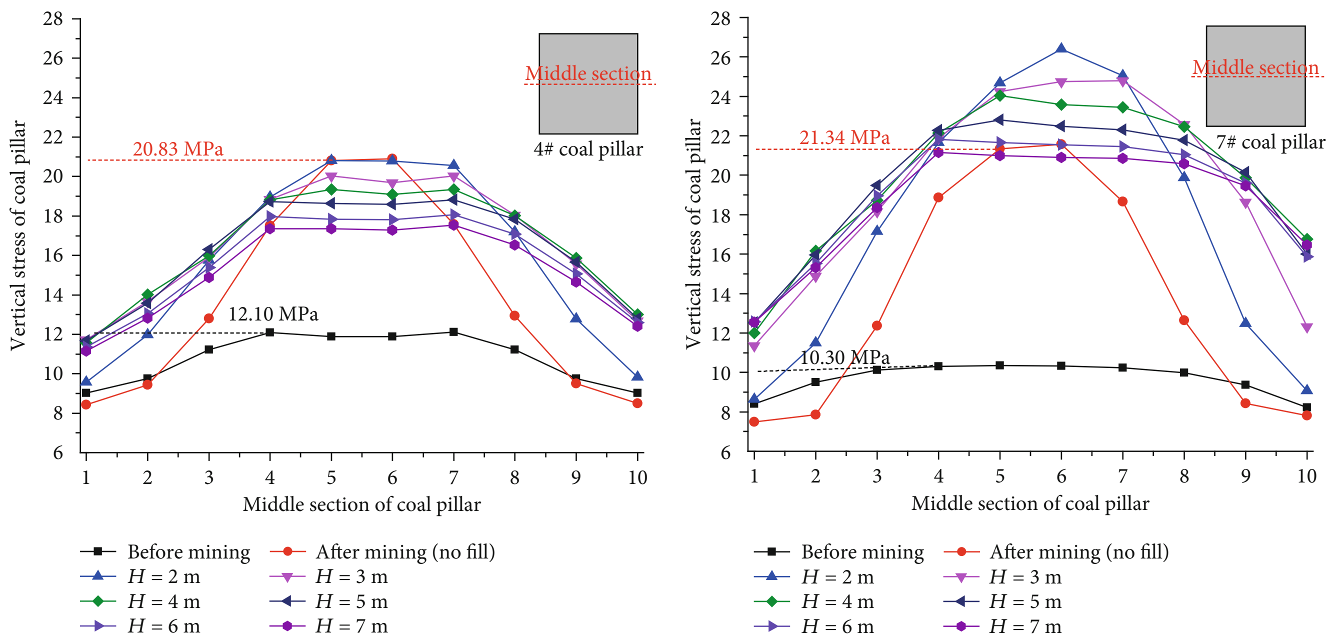


(f) Filling body heights 7 m

FIGURE 11: Vertical stress of coal pillars with different filling heights.

pillars. If certain reinforcement measures for the coal pillar are not taken, instability of the coal pillars below the no. 6107 working face will occur, causing the collapse of the no. 6107 working face and posing a huge threat to safe mining. Therefore, it is necessary to take reasonable measures to ensure the safe mining of the no. 6107 working face.

4.3. Influence Law of Filling Bodies on the Stability of Coal Pillars. Considering the mining conditions of the Yuanbaowan coal mine, the proposal of drilling on the floor of the no. 6107 working face and then grouting the goaf below the no. 6107 working face through these boreholes has been put forward. In order to ensure the safe mining, the effect of different heights of filling bodies on the stability of coal



(a) No. 4 coal pillar

(b) No. 7 coal pillar

Figure 12: Strengthening effect of different filling body heights on coal pillar's bearing capacity.

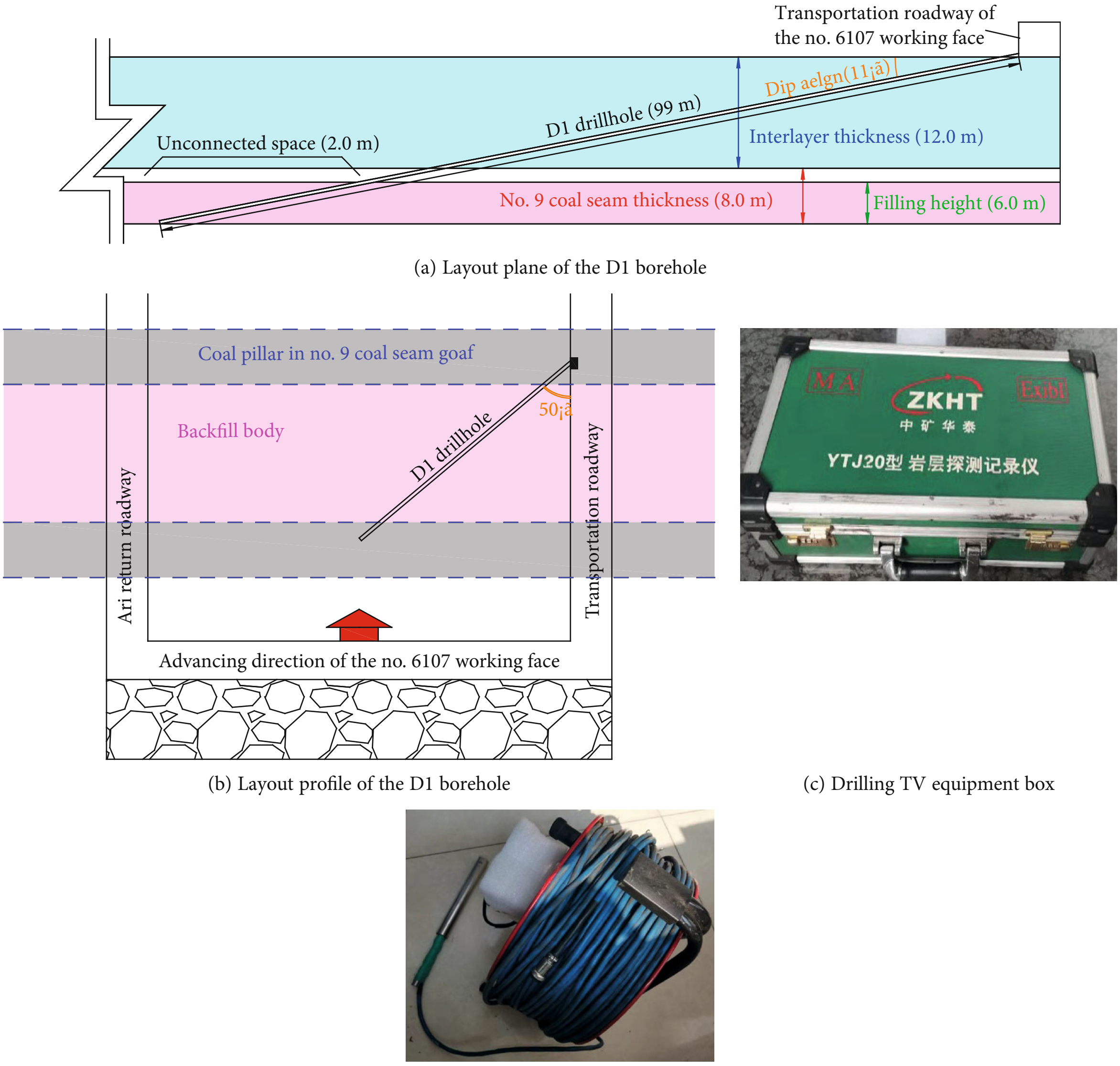
pillars is studied. The research is mainly divided into two aspects: (1) the effect of different filling bodies' heights on the suppression of the expansion of the coal pillars' plastic area and (2) the effect of difference in filling bodies' heights on strengthening the bearing capacity of the coal pillars. The grouting filling material used in the Yuanbaowan coal mine was encapsulated and brought to the laboratory to conduct the measurement of the physical and mechanical parameters. At the same time, to accurately reflect the interaction between the floor pillars and the filling bodies, the parameters of the filling materials in the numerical simulation are also calibrated to ensure that the mechanical properties reflected by the simulated parameters are consistent with the true mechanical characteristics of the grouting material. And the calibration results are shown in Figure 8.

4.3.1. Suppressing Effect of Filling Bodies on the Expansion of the Coal Pillars' Plastic Area. Under the influence of the clamping effect of the filling bodies, the proportion of the plastic zone and the horizontal side heaves of coal pillars are effectively suppressed. The suppression effect when the height of the filling body is 4 m is shown in Figure 9.

The elastoplastic expansion law of the coal pillars below the no. 6107 working face and the change law of the horizontal side heaves corresponding to different grouting heights are shown in Figure 10. As shown in Figures 10(a) and 10(b), the proportion of the plastic zone of the no. 1 to no. 7 coal pillars has been reduced to 18%, 36%, 45%, 47%, 46%, 44%, and 25% rapidly when the height of filling bodies reaches 2 m, 3 m, 4 m, 5 m, 6 m, and 7 m, respectively, compared to the unfilled state. The horizontal side heave of the no. 1 to no. 7 coal pillars rapidly has been reduced from 476 mm, 616 mm, 769 mm, 622 mm, 1063 mm, 1372 mm, and 1543 mm to 223 mm, 253 mm, 278 mm, 290 mm, 280 mm, 256 mm, and 230 mm, respectively, as shown in Figure 10(c). With the increase in the height of the filling bodies, the lateral clamping effect of the filling bodies on coal pillars below the no. 6107 working face tends to be more obvious, and the filling bodies have a significant suppressing effect on the expansion of both the plastic zone and the horizontal side heave of the floor coal pillars.

4.3.2. Strengthening Effect of the Filling Body on the Bearing Capacity of the Coal Pillar. The filling bodies of different heights form different clamping pressures on the coal pillars, which effectively improves the bearing capacity of the coal pillars, as shown in Figure 11.

In view of the limited space, taking the no. 4 and no. 7 coal pillars as examples, the strengthening effect of different heights of filling bodies on the bearing capacity of the floor coal pillars will be illustrated, as shown in Figure 12. It can be seen that before the mining of the no. 6107 working face, the vertical stresses of the no. 4 and no. 7 coal pillars are 12.10 MPa and 10.30 MPa, respectively, and the elastic core area accounts for 60% and 95%, respectively. Thus, the coal pillars are in a stable state. When mining is conducted without filling, the vertical stresses of the no. 4 and no. 7 coal pillars increase to 20.83 MPa and 21.34 MPa, respectively, and during which time, the proportions of the elastic core area of the two dramatically drop to 18% and 12%, causing instability for both these two coal pillars. While if the mining work of the working face 6107 is carried out after filling, the filling bodies support the overlying strata to a certain extent, reducing the overburden load of the coal pillars and increasing the proportion of the elastic core area of coal pillars, then the bearing capacity of coal pillars will be effectively improved.



(a) Layout plane of the D1 borehole

(b) Layout profile of the D1 borehole

(c) Drilling TV equipment box

(d) Television borehole camera and cables

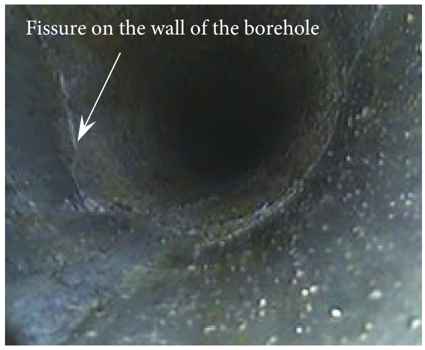
FIGURE 13: D1 borehole layout diagram and borehole TV observation equipment.

The strengthening effect of the filling bodies on the bearing capacity of the floor pillars becomes more obvious with the increasing height of the filling bodies.

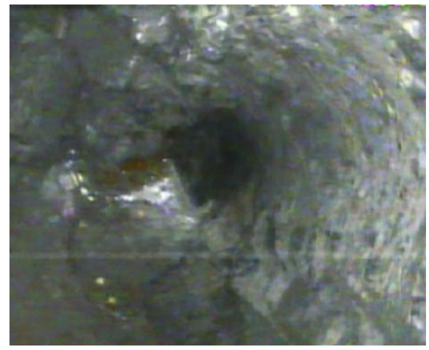
5. Engineering Practice

Based on the research results above, it can be found that when the height of the filling bodies reaches 5 m, 6 m, or 7 m, the coal pillars can be kept stable under the influence of abutment pressure of the no. 6107 working face. However, when the height of the filling body is 5 m, the elastic core area of no. 4 and no. 5 coal pillars accounts for 40.625%, which is in a critically stable state. The filling body may suffer from certain shrinkage in size during the consolidation process, causing fissures between the body and the coal pillar, and the lateral clamping effect of the filling body on the coal pillar will be weakened. When the height of the filling body is 6 m or 7 m, the proportion of the elastic core area of each floor pillar is higher than 50%, which can maintain the stability of the floor pillar. In summary, to ensure the safe mining of the no. 6107 working face with minimum filling cost, the height of the filling body is finally determined to be 6 m, and accordingly, on-site filling experiment work has been carried out.

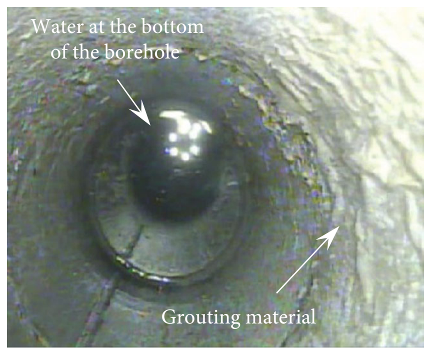
5.1. Observation Hole Layout and Observation Equipment. Drilling on the floor is applied to test the on-site filling result and to evaluate the disturbance and damage caused by the mining-induced stress during the mining process of the no. 6107 working face. A floor sight borehole (hereinafter referred to as the D1 borehole), whose diameter and length are 65 mm and about 99 m, respectively, has been arranged in the transporting roadway in the no. 6107 working face. The angle between the D1 borehole and transporting roadway is about 50°, and the horizontal angle of the drilling hole is about 11°. To ensure that the probe can be smoothly



(a) Floor of the no. 6107 working face



(b) Coal pillar



(c) Filling body

Figure 14: D1 borehole TV observation results at different depths.

lowered and determine the lowering distance of the probe, the connectable push rod is used to connect with the television borehole camera. As each part of the push rod is 1 m long, the lowering distance can be measured by the number of rods pushed into the drilling hole. The position of the borehole, D1, and drilling observation equipment are shown in Figure 13.

5.2. Field Observation Results. After the completion of the filling work and the consolidation of the filling slurry, developing rules of mining-induced fissures of the floor of the no. 6107 working face, the coal pillars, and the filling bodies have been investigated by using the borehole D1 and TV observation equipment, and their stability has been evaluated. On September 19, 2019, the underground borehole TV observation was conducted. At this time, the no. 6107 working face was about 30 m away from the borehole. The borehole successively goes through the floor, filling bodies, and coal pillars. The development conditions of fissures at different depths in the borehole D1 have been shown in Figure 14. The wall of the borehole D1 remains intact in the floor pillars and the filling bodies. There is much water in the bottom of D1, of which the seepage flow is relatively slow, and there is no obvious damage or water-conducting fissures. This also confirms that although the positions of the floor coal pillars, filling bodies, and floor coal pillars are located in the influence area of the peak value of abutment pressure of the no. 6107 working face, their stability is still maintained. It can be seen that the safe mining of the no. 6107 working face can be ensured when the height of the filling bodies reaches 6 m.

6. Discussion

(1) On the basis of ensuring that the physical and mechanical parameters of simulated materials are consistent with those of coal pillars and the filling bodies, the effects of difference in filling bodies' heights on the suppression of the expansion of the coal pillars' plastic area below the no. 6107 working face and on strengthening the bearing capacity of the coal pillars have been mainly investigated, and the influence laws of different grouting heights of filling bodies on the stability of coal pillars have been revealed. However, the consolidation process of the filling slurry, the degree of adhesiveness/bonding between the filling bodies and the side wall of the coal pillars, and the size of the clearage between the two remain to be studied. In addition, the variation of the lateral clamping of coal pillars with different bonding levels needs to be further studied.

(2) The filling materials of the Yuanbaowan coal mine are used, and accordingly, parameter calibration and simulation research is conducted in this paper. The effects of difference in the materials and the material ratio of filling bodies on the suppression of the expansion of the coal pillars' plastic area and on strengthening the bearing capacity of the coal pillars also remain to be investigated. Accordingly, research on the materials will be performed to find out the optimal combination of mining economic benefits

and coal pillar's controlling effects. The economic investment of the filling process will be minimized on the premise of ensuring safe mining.

7. Conclusion

(1) Before the mining of the no. 6107 working face, the elastic core areas of no. 1 to no. 7 coal pillars, which are all stable, accounted for 98%, 76%, 63%, 60%, 63%, 71%, and 95%, respectively. When mining is conducted without filling the goaf, the plastic zone of the no. 1 to no. 7 coal pillars expands rapidly as influenced by the front abutment pressure, and the proportions of the elastic core area of the seven dramatically drop to 46%, 27%, 20%, 18%, 14%, 12%, and 12%, respectively, causing instability for no. 2 to no. 7 coal pillars. Thus, filling the goaf in the no. 9 coal seam is the prerequisite for safe mining of the no. 6107 working face.

(2) The filling bodies have a certain lateral clamping effect on the coal pillars, which can effectively improve the stability of the coal pillars under the influence of the mining-induced pressure of the no. 6107 working face. The filling body has not only a suppressing effect on the expansion of the plastic zone of the coal pillars and the horizontal side heave but also a strengthening effect on the bearing capacity of the coal pillars. This phenomenon becomes more obvious with the increasing height of the filling bodies. When the height of the filling bodies reaches 6 m, the proportion of the plastic zone declines from 88% to 25% and the amount of the horizontal side heave reduced from 1534 mm to 230 mm. So the suppression effect on the plastic zone and the amount of the horizontal side heave is as high as 72% and 85%, respectively.

(3) Drilling on the floor of the no. 6107 working face and then grouting the goaf have been carried out. The research shows that when the height of the filling bodies is 6 m, the occurrence and expansion of mining-induced fissures in the floor strata, filling bodies, and the floor pillars below the no. 6107 working face have been effectively restrained. So the floor pillars remain stable under the influence of the front abutment pressure, and the safe mining above the goaf of the no. 6107 working face can be ensured by grouting the goaf first.

Data Availability

Research data can be seen in the relevant images and tables in the text.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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