

Research Article

Study on Rib Sloughage Prevention Based on Geological Structure Exploration and Deep Borehole Grouting in Front Abutment Zones

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Received 21 December 2019; Revised 2 September 2020; Accepted 7 September 2020; Published 22 September 2020

Academic Editor: Mohammad Sarmadivaleh

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This research presents the grouting method of preventing rib sloughage which severely impacts mine safety and longwall retreat speed in thick coal seam with numerical simulation and laboratory tests. Based on the analysis of the plastic failure mode of five types of coal seam, roof strata ahead of the longwall face, and fractures developed in the coal seam, the following results are drawn, the range and degree of plastic failure generated in the coal seam and roof strata ahead of the longwall face gradually decreased as the coal mass strength increased; the grouting boreholes are essentially laid out within the coal rib instead of the roof. For a particular case of a coal mine in Shanxi province, a novel cement-based material was grouted, which fulfilled the reinforcement requirements under the tectonic stress regions and front abutment zones. Besides, the grouting borehole construction requested predrilled boreholes, full borehole intubation, lengthened hole sealing, and multiple-step drilling and grouting. This study can provide a theoretical framework of a design overview and practical basis for similar mining conditions in other coalfields.

1. Introduction

Thick coal seam (thickness ≥ 3.5 m) resource reserves account for 44% of the total coal supply in China and constitute more than 45% of the total output [1]. Continuous improvement of coal mining technology, coal mining equipment innovation, and ground control theory and technology research related to high-intensity mining all enable an extensive application of the thick seam mining techniques in China. The majority of the 10 million-ton mines in China have been employing the thick seam mining method [2]. The advantages of the thick seam mining, such as a high recovery rate and an uncomplicated underground mining layout, have been acknowledged. However, increased mining and longwall height have generated many coal rib issues and can be incredibly challenging to control. Rib sloughage and roof collapse along the longwall face often occur during the

mining process, especially when encountering adverse geological conditions such as faults, collapsed columns, and topple mining zones. In the minor accident, powered support topples over; in the serious accident, large-area roof caving happens, which seriously decreases advancing speed and may even cause unexpected casualties. These adverse effects greatly limit the development of thick seam mining and restrict the mining efficiency of the associated thick seam equipment [3–5].

Studies on rib sloughage mechanisms of thick seam mining and its prevention techniques have recently been initiated and conducted worldwide. Bai et al. [6, 7] simulated the mechanism of longwall face spalling and verified by field observation and constructed 2D finite difference models in order to simulate the longwall goaf compaction process. The proper mining-induced stress around the longwall face was obtained. Song and Chugh [8] performed a three-

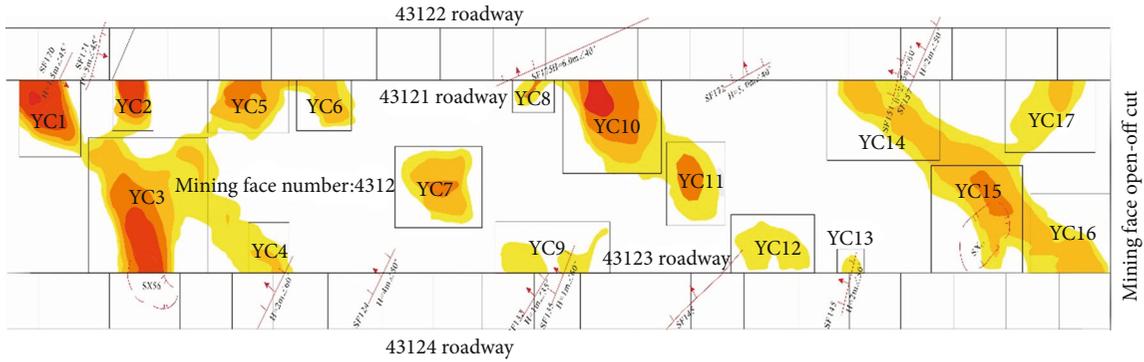


FIGURE 1: Detection results of geological structures.

dimensional analysis of the stability of a thick coal seam longwall working face. Yang et al. [9], in order to solve the instability problem of the longwall face, presented a new grouting technology of flexible bolts to reinforce the coal wall and improve the longwall face stability. Bai and Shihao [10] summarized the research status of mining-induced fractures near the working face, which are essential to note due to potential instability problems encountered during the mining process due to fracturing of the working face. Guo et al. [11] established a conceptual model of support and surrounding rock under different structural conditions of the main roof to study the interaction of the coal wall, support, and roof. As of now, many studies have focused on the mechanism of postrib sloughage treatment rather than prevention or precaution. In particular, the prevention of longwall rib sloughage in tectonic stress regions has not been carefully considered.

The primary purpose of this study is to develop a method of preventing rib sloughage under specific abnormal geological conditions and front abutment zones. Considering the disadvantages of polyurethane, such as high cost and heat generation, a new type of cement-based grouting reinforcement material with a low cost and reaction temperature has been developed. A site test at a thick seam mine was conducted with this new material, and rib sloughage in this longwall face has been successfully prevented, which indicates that the technique of rib sloughage prevention based on geological structure exploration and deep hole grouting in the front abutment zones is applicable and feasible [2–4, 6, 8]. This study reports the field results of this new technique.

2. Project Overview

The layout of longwall panel 4312 of a mine in Shanxi province is shown in Figure 1. The longwall panel adopting three entries is 1714.9 m long and 220.7 m wide. The cross-sections of these three entries are 5.4 m wide \times 3.8 m high, 5.4 m wide \times 5.4 m high, and 5.4 m wide \times 5.6 m high, respectively. The seam thickness is approximately 5.5 m. The inclination angle of the coal seam is 1–7° and 4° on average. The coal seam alternates soft-hard-soft from top to bottom and appears to overall be soft and loose. The roof parting is an easily broken mudstone and susceptible to weathering.

Additionally, numerous unpredictable mini geological structures are present, incurring a large-area roof caving and severe rib sloughage, and adversely affect the advancement rate of the longwall face. Severe differential roof movement and rib sloughage often occur when mining in the vicinity of geological structures and/or the roof partings. A detailed prescription of the geological structures is shown in Figure 1. When the mining height exceeds 5.5 m, the shield can no longer adequately support the roof, and a long-term lack of support of the rib and roof can induce large-area roof caving. When rib sloughage along the face is significant, and if hydraulic props are utilized with I-beams or wood blocks as temporary support, manual operation is required along the coal rib, which causes personal safety issues and poor support results.

3. Slot Wave Detection Technique in the Geological Abnormality Region

3.1. Slot Wave Detection Technique. As a unique geologic exploration method, slot wave seismic exploration is a new geophysical method that utilizes a waveguide activated and transmitted into the coal seam to detect the discontinuity of the coal seam via penetration and reflection measurements. It is a subfield of seismic exploration. Slot wave seismic exploration has been characterized as providing a wide detection range, high precision, intense capability of antielectromagnetic interference, easy waveform identification, and intuitive visual results.

3.2. Detection Results and Analysis. Reflection and transmission are the two primary methods of underground slot wave detection. In this analysis, the transmission method was utilized [12, 13]. In this experiment, the seismic origin and the wave detector were placed in the same entry (Figure 2). The reflection principle of the in-seam wave is to confirm the discontinuity of the coal seam in front according to receiving the nonroadway reflected in-seam wave. When the fault throw is close to or greater than the thickness of the coal seam, the waveguide will be blocked entirely, and a distinctive slot wave reflection will return. When the fault throw is small, the received slot wave signal will be accordingly weakened. When the fault throw is very small or absent, the wave detector will not receive a reflected slot wave. The reflection of the

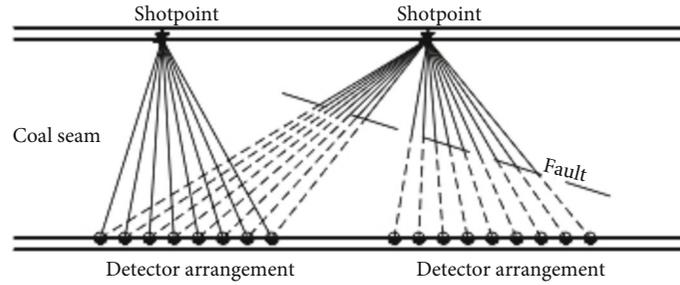


FIGURE 2: Principle of the transmission method.

entry is easy to determine and will not be considered during the operation. The detection result is shown in Figure 1. Description of areas with abnormalities is shown in Table 1. The exploration length was 1670 m and was divided into six sections for transmission detection. A total of 17 areas with geological abnormalities were detected.

4. Deep Borehole Grouting in the Front Abutment Zone

4.1. Analysis of the Borehole Layout. Rib sloughage and spalling along the longwall face and the generation of a cavity in the face roof primarily occur as the following process [14–16]: firstly, coal wall spalling along the face occurs; secondly, the roof above the face loses the support from the wall, and a leaky top/cavity is generated; and thirdly, the shield support has less contact with the roof, which leads to the decline of the support capacity of the roof, causing further rib sloughage/spalling, and an expanding top cavity. As this trend continues, the longwall face has to continuously rise in order to have contact between the shield and the roof, which in turn severely affects safety during production. Overall, rib sloughage/spalling along the face is the primary cause of roof instability. At this point, reinforcing the coal wall is key to controlling the roof stability. The frequency and intensity of coal wall spalling can be reduced by increasing the stability of the coal wall, thus minimizing rib spalling and the size of the cavity developing in the roof. It can be summarized as “covering the anomaly area, focusing on the coal rib, and considering the roof.”

To further examine the importance of rib sloughage for roof control, a 2D numerical model simulation was conducted. Fixed constraints were applied at the bottom of the model, and horizontal displacement constraints were applied at the sides. Weight stress boundary conditions such as overburden were applied at the overburden. The size of the model was determined according to the geological conditions of the actual working face, with a length of 2000 m, a width of 350 m, and a height of 150 m. The numerical model is shown in Figure 3. The failure criterion used the Mohr-Coulomb (M-C) criterion. The surrounding rock failure of the working face when it was mined back 500 m was selected as the mining goal. The section along the middle section of the working face was used to compare and analyze the calculation results of each plan. A plastic failure zone developed in the front of the face and roof strata was analyzed with various strength

TABLE 1: Description of areas with abnormalities.

Serial no.	Description
YC1	SF170, SF171 fault extension
YC2	Collapsed column
YC3	SX56 collapsed column and regional weak water enrichment
YC4	SF119 fault extension
YC5	Fault or broken coal strata
YC6	Fault or broken coal strata
YC7	Collapsed column or SF124, SF175 fault extension, possible regional water enrichment
YC8	SF175 fault extension
YC9	Fault or broken coal strata
YC10	SF132, SF134 fault extension
YC11	Collapsed column or SF172 fault extension
YC12	SF143 fault extension
YC13	SF145 fault extension
YC14	SF161, SF157 fault extension and possible regional weak water enrichment
YC15	SX63 collapsed column and possible regional weak water enrichment
YC16	Broken coal strata or stress concentration region
YC17	Broken coal strata or stress concentration region

parameters of the coal mass. The parameters are shown in Table 2.

Figure 4 shows that, with a continuous increase in coal strength, the level and extent of the plastic failure zone gradually reduced in the front of the longwall face and roof strata. Schemes 1-4 show that the plastic zone in the front of the face reduced from 3.5 m to 2.0 m, and the width of the roof plastic failure zone decreased from 7.0 m to 2.0 m. With an increase in coal strength, the plastic failure mode changed from being a complicated failure to simple tensile strength and shearing damage. The overall degree of plastic damage substantially decreased as well. Therefore, the probability of coal wall spalling and a cavity developing in the roof significantly reduces.

Scheme 5 indicates that the plastic failure zone of the roof strata was not reduced compared to that of Scheme 1. The analysis results from the numerical modeling suggest that, although the strength parameters of roof strata increased, the strength of the coal mass ahead of the mining face is

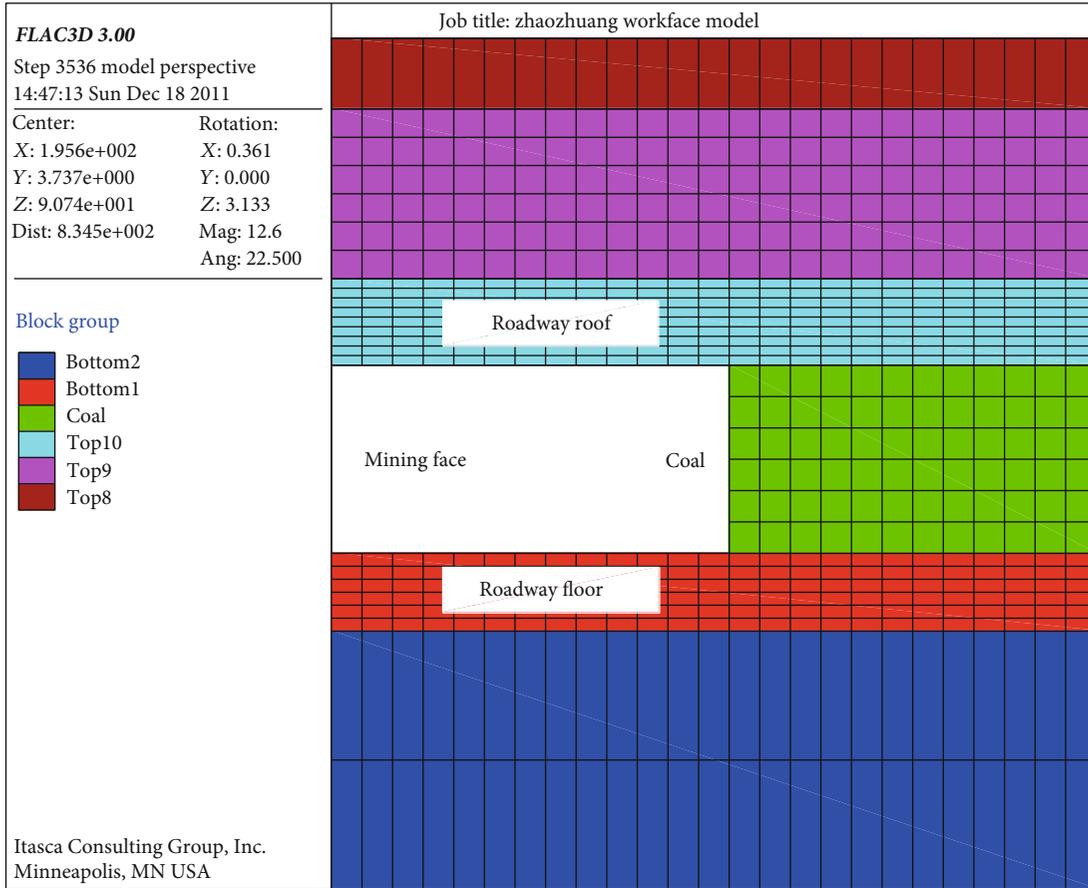


FIGURE 3: Numerical model diagram.

TABLE 2: Coal parameters.

Coal parameter	Volume modulus (GPa)	Shear modulus (GPa)	Internal friction angle (°)	Cohesion	Body force
Scheme 1	6.9	0.2	12	5.3	1400
Scheme 2	7.9	1.2	15	7.3	1400
Scheme 3	8.9	2.2	18	8.3	1400
Scheme 4	9.9	3.2	21	9.3	1400
Scheme 5	The coal parameters are the same as those used in Scheme 1; the direct roof rock parameters are increased by 50% to compare to Scheme 1				

not sufficient and could not provide adequate support to the roof strata, which further leads to postfailure tensile damage in most of the plastic failure regions of the roof strata. Solely relying on the reinforcement of the roof strata is not a reliable solution to spalling and a leaky top of the coal wall.

Overall, increasing the strength of the coal mass not only can improve the strength of the coal wall and reduce coal wall spalling but also is influential in the roof support because it can effectively lessen plastic damage to the roof strata. This could minimize the occurrence of a leaky top and cavity development. It was also confirmed that rib sloughage along the longwall face play a significant role in roof collapse. Therefore, the middle and upper sections of the coal seam

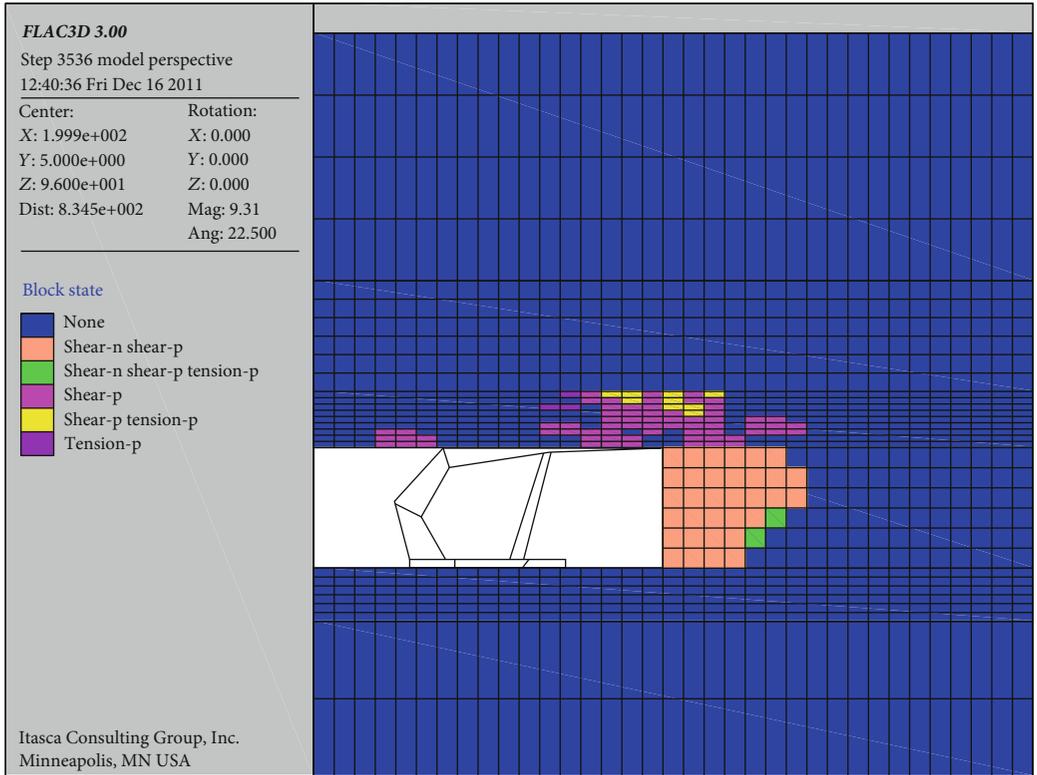
should be the primary focus when considering borehole grouting with the principle of “covering the anomalous area, focusing on the coal rib, and considering the roof.”

4.2. Analysis of Borehole Operation

4.2.1. Implementation in Advance. Deep borehole grouting in a large mining height face can effectively prevent coal wall spalling and roof collapse and has the least impact on the overall production of the working face. However, the original coal mass has poor groutability and grouting effects. Groutability can be improved while the coal mass could develop more cracks when experiencing the front abutment pressure. When deep hole drilling and grouting is implemented in the zone of influence of the front abutment pressure, better grouting results can be obtained.

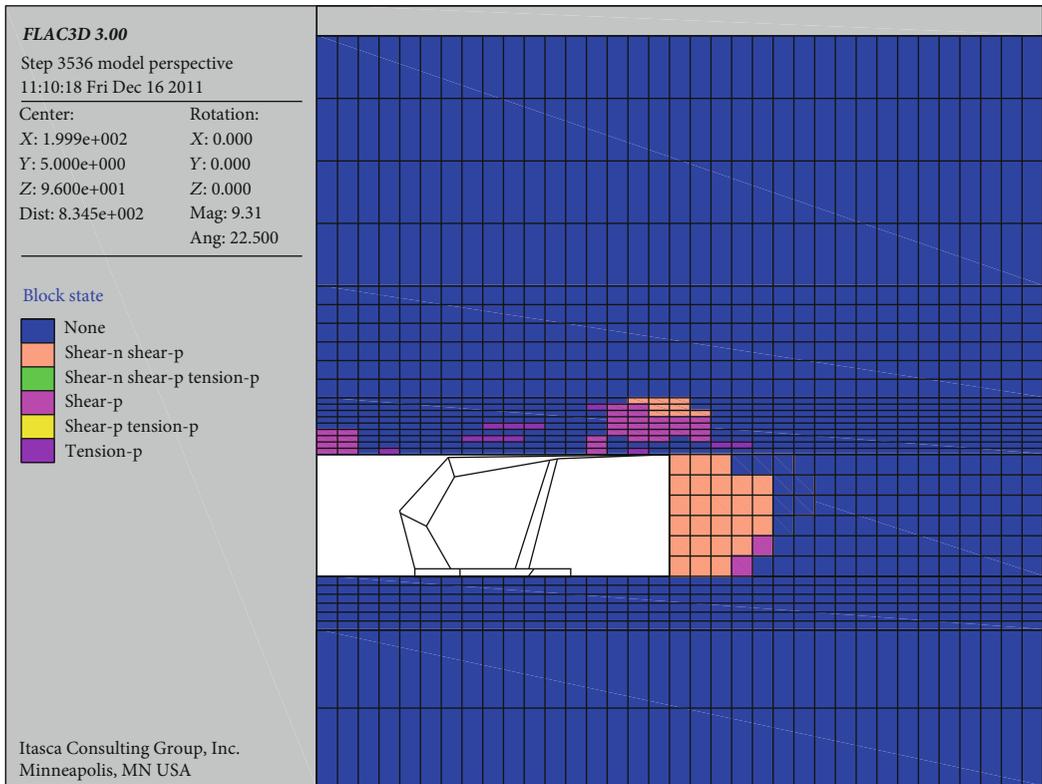
4.2.2. Full Hole Intubation and Lengthened Hole Sealing. After a deep hole is drilled, a full-length polyethylene (PE) or polyvinyl chloride (PVC) grouting pipe is inserted; a steel pipe is used on the hole sealing segment, which is longer than 10 m; and a two-component grouting material is utilized for the hole sealing. When the grout-stop-layer of the sealing stage is reached, a single-component grout material is utilized to reinforce grouting in the deep layer.

4.2.3. Multistep Borehole Formation and Split Grouting. It is challenging to drill boreholes and inject grouting materials



Scheme 1

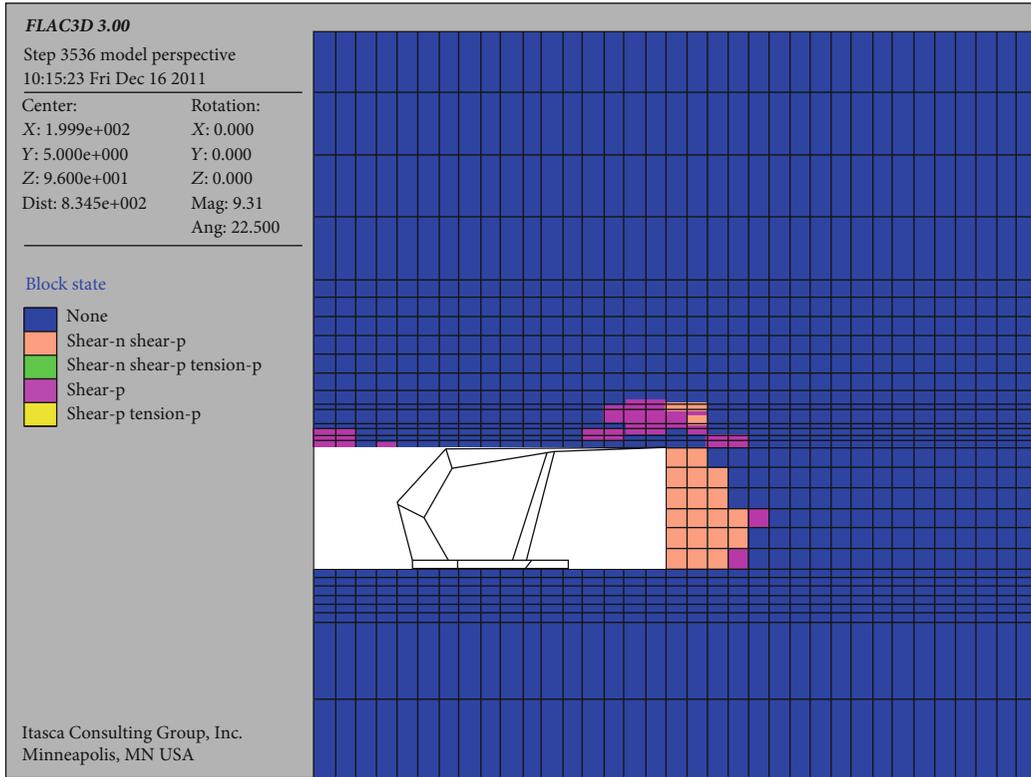
(a)



Scheme 2

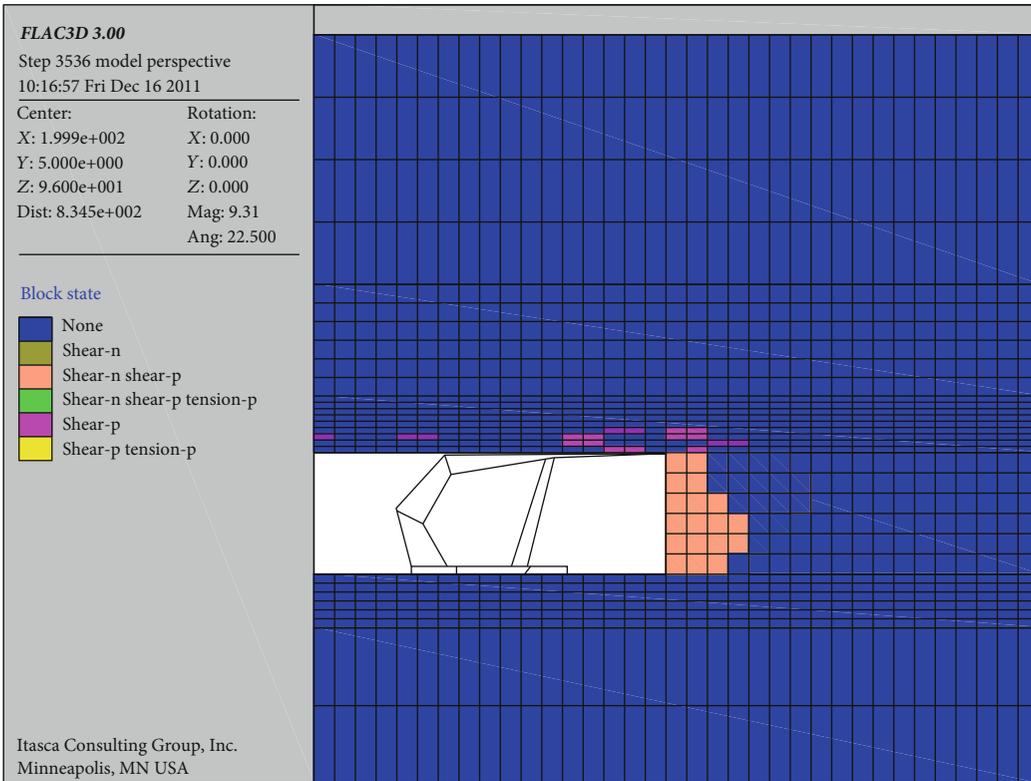
(b)

FIGURE 4: Continued.



Scheme 3

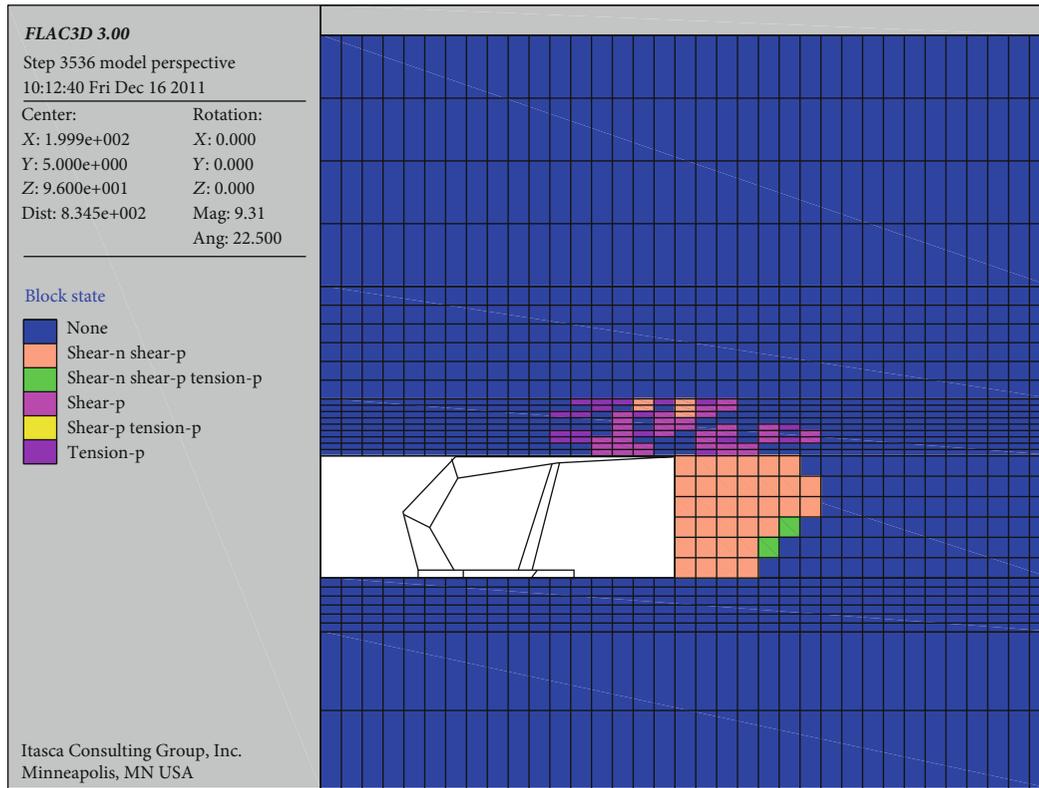
(c)



Scheme 4

(d)

FIGURE 4: Continued.



Scheme 5
(e)

FIGURE 4: Numerical simulation results.

in the vicinity of the front abutment zone due to fractures and cracks that have developed in the coal mass and roof strata. These interlaced fractures and cracks will incur difficulties in borehole formation and result in severe grouting leakage during the process of borehole grouting. To minimize the difficulty in borehole formation and grouting leakage, the technique of multistep borehole formation and split grouting has been developed and conducted with the following procedure. The split grouting device is shown in Figure 5.

- (a) Set up the equipment for borehole drilling and grouting in place, and prepare for drilling
- (b) Drill 3 m deep with a Φ 133 mm drill bit first, and then remove the drill and insert the sleeve. The sleeve is divided into two 1.5 m sections. A high-pressure flange is welded to the outer end of the sleeve
- (c) After sleeve insertion, the flange is connected for single grouting. Then, the hole opening is reinforced, and the gap around the sleeve is filled
- (d) One hour after the grouting, a Φ 75 mm drill bit is utilized to drill a hole in the sleeve. If no returning water is present or bit jamming occurs when the borehole depth is far less than the predefined depth, the drill bit should be pulled back. After the flange is reinstalled, the grout and sleeve should be placed

into the hole again, and the grouting and sleeving process should be repeated until the designated drilling depth is reached

- (e) The process of inserting the pipe, sealing the hole, and grouting should be deployed when the borehole reaches the designated depth. A steel pipe is placed 10 mm outside the borehole, and the PVC pipe is used internally. The hole sealing length is 10 m

4.3. Grouting Parameters. The water-cement ratio of the grouting material plays a significant role in ensuring the reinforcement quality. The water-cement ratio of 0.6:1 is adopted for the single-solution grouting material during site construction, and the double-solution grouting material used for drill hole sealing has a water-cement ratio of 0.8:1.

Grouting pressure is another significant parameter that affects the grouting results. Under normal circumstances, the grouting pressure of a deep borehole is 20-25 MPa. In the case of a damaged or severely leaky surrounding rock conditions, the pressure can be 15-20 MPa. The deep borehole grouting pressure normally regulates the pump pressure according to the grouting rate. In this experiment, the maximum ultradeep borehole grouting pressure reached 27 MPa, and the minimum pressure was 24 MPa.

Principally, single-hole grouting should be conducted until the pressure meets the limit. If the grouting time is too long or the grouting volume is too large, these typically

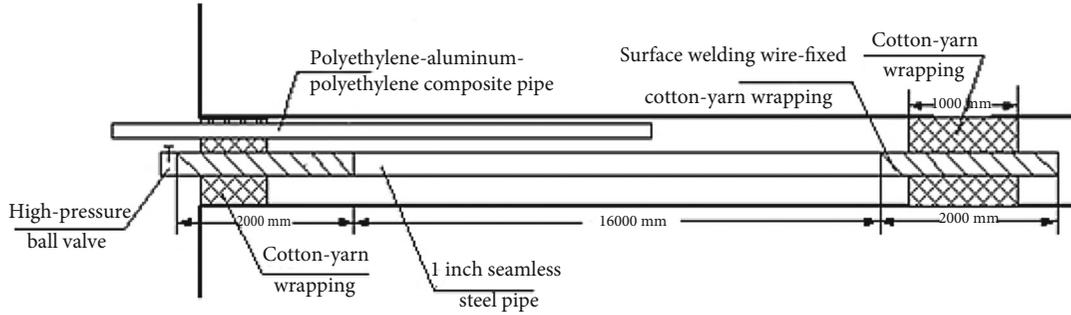


FIGURE 5: Split grouting device.

suggest the presence of leaky channels (i.e., fractures, cracks, or faults). Based on the site measurements, the maximum single-hole grouting volume of the ultralong borehole grouting was 15.15 tons in this experiment.

4.4. Deep Borehole Grouting Timing. The primary purposes of the analysis and selection of a suitable grouting timing and the grouting zone of the longwall face for deep borehole grouting are to examine the groutability of the grouting liquid, provide consistency between the grouting time and the grouting liquid properties, and enhance the degree of cementing between the grouting liquid and the coal rock mass, thus enhancing the grouting reinforcement results.

A total of 34 boreholes were drilled in the entry of a large height longwall face. The borehole diameter was 75 mm, and the spacing between these boreholes was 5 m. The final drilling depth was between 70 and 80 m, as shown in Figure 6.

To accurately obtain measurements of the borehole grouting volume at different distances from the face and to optimize the grouting time, six sets of grouting experiments were conducted for the arranged deep boreholes. The distances to the longwall face were 20 m, 25 m, 30 m, 35 m, 40 m, and 45 m, respectively. The grouting volumes of these six grouting experiment cases are shown in Figure 7.

Overall, larger borehole grouting volumes are from the second, third, fourth, and fifth sets of boreholes, and these holes are approximately 20–40 m away from the longwall face (Figure 7). This indicates that more fractures have developed in the coal mass within the range of 20–40 m from the face, as there is a large amount of leakage that occurred during the on-site grouting process. The grouting results also indicate that the coal mass is significantly affected by the front abutment pressure within 20–30 m ahead of the longwall face. As a result, it was determined that the deep hole grouting would be conducted when it is 30–40 m away from the longwall face.

4.5. Deep Borehole Grouting Material. Deep borehole grouting commences by drilling holes into the coal mass from each side of the panel. The drilling depth ranged from 50 m to 100 m. To effectively reinforce the potential geological structures in the coal, an innovative single-solution deep borehole grouting material has been developed. The basic material consists of a silicate cement and a compound admixture added to adjust the slurry properties. The final material ratio is as follows: 100% ultrafine 52.5 silicate cement, 2% compos-

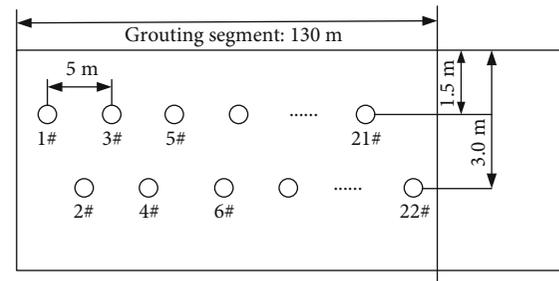


FIGURE 6: Layout of boreholes.

ite retarder, and 2% complex accelerator. The initial setting time of the slurry is 2.5 h, and the final setting time of the slurry is 8 h [17–20]. Figure 8 indicates the slurry performance and strength development process of the single-solution grouting material with a water-cement ratio of 0.6 : 1. The slurry extension is 226 mm at 0 min, with the time increasing; the slurry extension decreased to 182 mm at 100 min. The compressive strength of the single-solution grouting material can reach nearly 19 MPa at 1 d, 28 MPa at 3 d, and 32 MPa at 7 d.

When grouting in a shallow section of a hole where more cracks are present, a double-solution grouting material is used to ensure rapid condensation. The material consists of two sets of components, A and B, which are inorganic mineral powders. Water is added to each set of the components separately and stirred before mixing A and B. A single solution can be stored for longer than 6 h without bleeding and coagulation. The double-solution grout loses fluidity in 1–3 min after the two solutions are mixed and becomes fully solidified in 5–10 min. Figure 9 shows the strength development process of the double-solution grouting material at various water-cement ratios. When the water-cement ratio is 0.8 : 1, the uniaxial compressive strength can reach 8 MPa at 1 h and approximately 12 MPa in 2 h [21, 22].

4.6. Implementation of the Deep Hole Grouting and Results

4.6.1. Borehole Layout. Take the No. YC14 area shown in Figure 1 and Table 1 as an example to illustrate the borehole. A total of 22 boreholes were arranged in this area and divided into the upper and lower rows. As shown in Figure 10, the boreholes were positioned in a layout called “triangular crossing,” with the distance between adjacent holes of each row being 10 m. The boreholes were constructed using

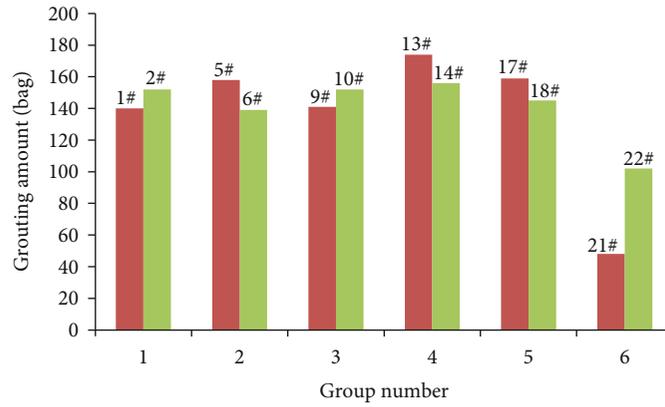


FIGURE 7: Borehole grouting volume for the boreholes drilled into the longwall working face.

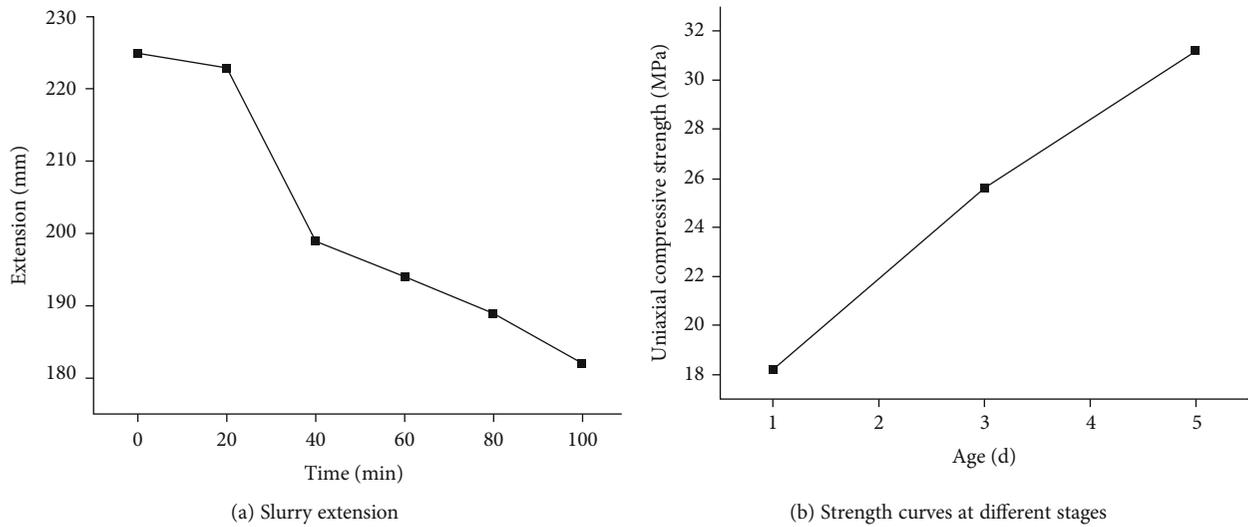


FIGURE 8: Slurry performance (water-cement ratio 0.6 : 1).

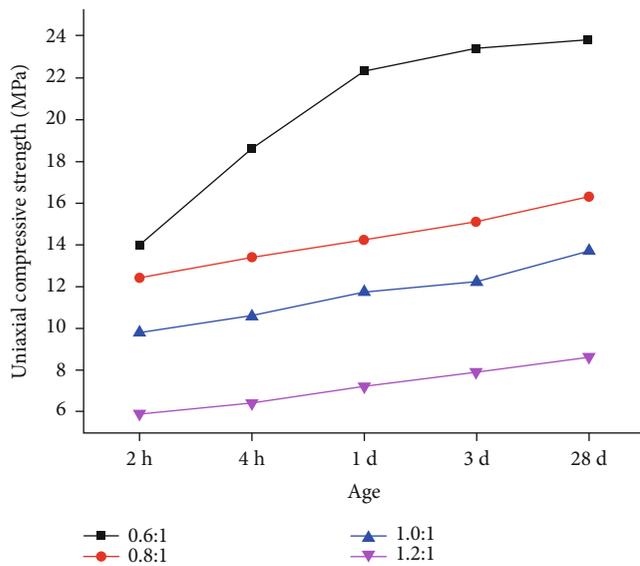


FIGURE 9: Strength development process of the new inorganic grouting material with varying water contents.

multistep drilling. A Φ 133 mm drill bit was used for the construction of the outer 8 m segment of the borehole, and a sleeve was installed after the completion of construction. A Φ 94 mm drill bit was used to construct the inner segment of the borehole. The drilling parameters are listed in Table 3.

4.6.2. *Grouting Results.* The status of the coal wall before and after grouting is shown in Figure 11.

The severe damage of the coal wall before grouting decreases the longwall retreating speed (Figure 11(a)). After grouting reinforcement, the coal wall remains integrated, and the rapid advancement of the longwall face was achieved (Figure 11(b)). This shows that the deep borehole grouting prevention method is effective at preventing damage to the coal seam.

After the longwall face reached the grouting area, site examination and statistical analysis were conducted to observe spalling and roof caving. According to the site observation, the coal mass integrity in the grouting reinforced area was significantly improved compared to that of the ungrouted area. Shown in Figure 12 are the comparative analysis results.

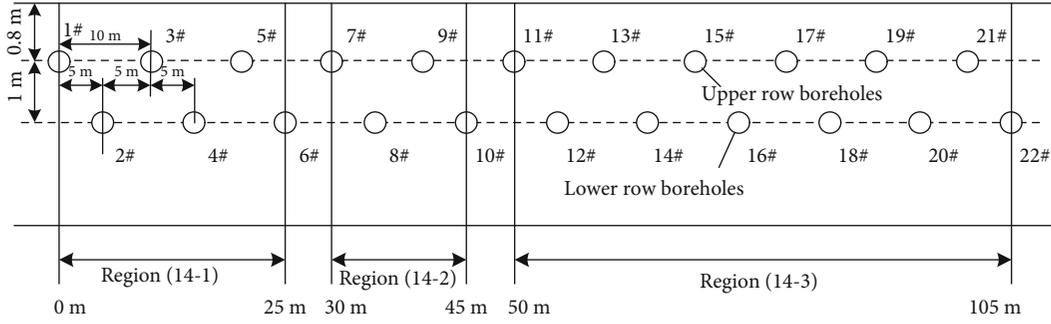


FIGURE 10: Layout of the boreholes.

TABLE 3: Parameters of the boreholes.

Borehole member	Borehole location	Borehole depth (m)	Borehole height (m)
1#, 3#, 5#	Upper row	100	0.8 m from the roof
2#, 4#, 6#	Lower row	100	1.8 m from the roof
7#, 9#	Upper row	70	0.8 m from the roof
8#, 10#	Lower row	70	1.8 m from the roof
11#, 13#, 15#, 17#, 19#, 21#	Upper row	60	0.8 m from the roof
12#, 14#, 16#, 18#, 20#, 22#	Lower row	60	1.8 m from the roof



(a) Before grouting



(b) After grouting

FIGURE 11: Rib sloughage status of the coal wall working face before and after grouting reinforcement.

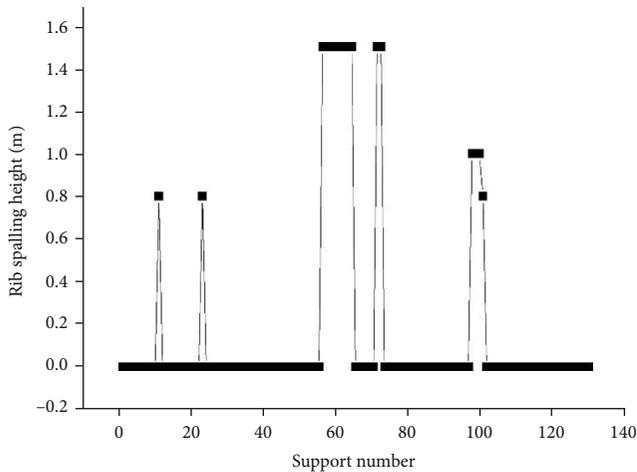


FIGURE 12: Rib sloughage data.

Support numbers 1-53# are the abnormal areas with grouting reinforcement while the others are normal areas. An abnormal area refers to a geological structure found within the working face, such as a fault and coal rock fracture zone. In this paper, grouting was performed in the abnormal areas, while the normal areas were not reinforced with grouting. Figure 12 shows that the coal wall integrity was considerably improved in the abnormal areas covered by a 100 m borehole. The area and height of rib sloughage were both significantly reduced. However, rib sloughage in the area without grouting reinforcement was very severe, especially in the 56-64# support region. The maximum spalling height was 1.5 m, and the maximum depth could reach as deep as 2 m, causing difficulties in roof control along the longwall face. Overall, grouting reinforcement can enhance the coal mass integrity in areas affected by geologic structures to improve the load capacity of the coal mass.

5. Conclusions

- (1) The numerical modeling results indicate that, as the coal mass strength increases, the degree and extent of plastic damage to the coal wall and roof strata of the longwall face gradually decreases. Increasing the coal strength of the working face can improve the coal wall strength and control the coal wall shingle, effectively reduce the degree of plastic failure in the roof strata, and control the roof leakage problem
- (2) The layout principle of boreholes for grouting involves “covering the anomalous area, focusing on the coal rib, and maintaining the roof.” The borehole construction principle involves “predrilled holes, full-length hole intubation, elongated hole sealing, multi-step borehole formation, and split grouting”
- (3) The experimental results of grouting materials show that the slurry extension is from 226 mm to 182 mm with the time increasing; the compressive strength of the single-solution grouting material can reach nearly 19 MPa at 1 d, 28 MPa at 3 d, and 32 MPa at 7 d. The newly developed grouting material can meet the grouting demands of both the shallow and deep zones of the front abutment pressure, and grouting reinforcement results indicate that it is very effective at enhancing the integrity of the coal seam
- (4) Grouting reinforcement can improve the integrity of the coal body in the abnormal area for the prevention mechanism. The chances and probability of coal wall spalling are greatly reduced after grouting. The deep borehole grouting method based on structural exploration and front abutment zones can effectively prevent coal wall rib sloughage/spalling

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was financially supported by the Henan innovative science and technology team support project (CXTD2017088), National Natural Science Foundation of China (51904093), Key scientific and technological projects in Henan Province (202102310217, 202102310544, 192102310247), and Key scientific research project plan of colleges and universities in Henan Province (20A440007).

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