High Mining Face Flexible Reinforcement to Prevent Coal Wall Spalling by Cuttable Aluminum–Plastic Pipe Pre-Grouting

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Abstract: A larger mining height leads to easy caving of the coal wall in the working face. The flexible reinforcement method during the mining period of the working face affects the normal mining of the working face, and the high strength of the traditional bolt/cable material affects the operation of the shearer drum, so it is necessary to seek a reinforcement material which does not affect the production and the drum coal cutting. This paper proposed a technical scheme of coal wall reinforcement by pre-grouting with a cuttable aluminum–plastic composite pipe which is easy to cut during mining in the working face, tested the mechanical properties of the “grouting + flexible pipe” specimen, and obtained the optimal support spacing by numerical simulation and carrying out an industrial test. The results show that the tensile strength of aluminum–plastic composite pipe is much higher than that of coal spalling and the elongation is much higher than that of the anchor rod. When double-row composite grouting holes are arranged 1.5 and 3.0 m away from the roof, the supporting effect is better. Underground grouting shows that pre-grouting before mining according to the advancing speed of the working face 10–14 days in advance can effectively fill the coal cracks and significantly improve the integrity of the coal wall.

Keywords: large mining height working face; coal wall spalling; advance pre-grouting; flexible reinforcement; aluminum–plastic composite pipe; numerical simulation

1. Introduction

In recent years, as China’s comprehensive mining equipment and mining management techniques have become more mature, the thickness of coal seam mining is increasing. The three main methods of mining thick coal seams in China are large mining height integrated mining technology, stratified mining technology, and top release coal mining technology [1]. Due to the many advantages of fully mechanized mining with large mining height, such as the high recovery rate and few relocations of fully mechanized mining equipment, it has gradually become one of the main means of thick coal seam mining. However, with the increasing mining height of the large mining height working face and under the action of coal wall and roof pressure, the leading supporting pressure of the coal wall and overlying strata also increases, which makes the stability of the coal wall in working face decrease [2,3]. Due to the influence of the geological structure and the lack of strength of the coal body of the large inclined coal seam, the coal wall of the working face was destroyed and the end face falls [4,5]. After the spalling phenomenon appears, the distance between the end faces increases because the support can not be advanced in time, which leads to roof fall accidents, threatening the safety of personnel and affecting the normal production schedule of the mine.
At present, the research on coal wall failure in large mining height working face at home and abroad mainly includes the factors of coal wall spalling, the failure mechanism of the coal wall, and the reinforcement technology of coal wall spalling in working face. Yuan et al. [6] put forward the technology of flexible reinforcement of coal wall spalling prevention by using brown rope, which can be better used as a means of coal seam spalling support and reduce the probability of working face spalling. Wang et al. [7] believed that with the increase of brace support strength, the probability of spalling of coal wall in working face decreases, and the depth of spalling is linear with support strength. Wang et al. [8] and Tian et al. [9] pointed out that when increasing the internal friction angle and hardness of the coal wall in the working face, the maximum failure depth and the probability of spalling of the coal wall in the working face will decrease. Li et al. [10] pointed out that under the condition of high roof and floor strength of the coal seam, the failure of coal wall spalling is controlled by the geological structure and in situ stress, which can be divided into the following failure forms: compression-shear slip type, gravity slip type, vertical spalling type, and hourglass type. Yang et al. [11] pointed out that the failure of coal walls in large mining height working faces is mainly divided into tensile cracks and shear failure, which is mainly due to the upper load of coal wall in the working face, which leads to the tensile stress and compressive stress exceeding the ultimate strength of coal body. Bai et al. [12,13] explained the causes of coal wall spalling from the point of view of stress and plastic deformation of the coal seam. The research shows that when the coal mass in the working face is subjected to high shear deformation, the weakening point or surface appears in the working face, and spalling failure occurs. Martin et al. [14] developed a flexible tubular device that can coordinate with conventional roof bolts, which is used to control the large deformation of coal walls during longwall retreat mining, which is conducive to improving the stability of the coal wall. Wang et al. [15] studied the reasonable drilling position and parameters of coal wall grouting reinforcement in the coal seam with gangue and obtained that the best hole arrangement position is that the grouting hole should be consistent with the starting point of coal wall failure.

However, the current research focuses on the emergency treatment after the spalling accident in the working face, while less research has been conducted on coal body reforma-
tion prior to back mining. As we all know, the treatment after spalling has a great influence on the advancing speed of the working face, the operation safety is poor, and the labor intensity of workers is high [16]. However, the method of pre-grouting from the upper and lower lanes ahead of the working face at a certain distance before mining in the working face makes full use of the advantages of roadway layout in the mining area to reinforce the coal in front of the working face, which does not affect the production but also leaves enough time for the strength of grouting materials to rise so that the grouting work can really play its role by effectively preventing spalling, ensuring the safety of operation and the recovery efficiency, and it also has great technical and economic advantages. Nowadays, the widely used supporting materials are mostly developed for the spalling accident treatment of the working face, which is not suitable for the advanced pre-grouting technology of the working face [17], such as the widely used chemical slurry, double-liquid grouting, anchor rod/anchor cable, etc. Among them, organic chemical pulp has high strength and quick solidification, which is a widely used means to control spalling. However, due to the fast advancement speed, the chemical slurry is cut off before it reaches its maximum strength, resulting in some waste [18]. In addition, the admixture of chemical slurry has a greater impact on the coal quality and is not suitable for mass use. Two-liquid grouting for cement-based materials has a wide application range but compared with chemical grout, the setting speed is slower, the adaptability of grouting for working face after spalling is poor, and the admixture of water glass affects the long-term strength of cement-based materials. The strength of the anchor rod and anchor cable is too high for the coal miner to cut the anchor rod/anchor cable off, requiring special measures to be used to deal with it, which seriously affects production [19]. To sum up, the existing supporting materials are not suitable for coal reinforcement by pre-grouting in advance.
In this paper, the change law of coal force near the working face with space and time is fully studied, the factors and failure forms of coal wall spalling are analyzed, the layered flexible reinforcement technology of advanced pre-grouting in large mining height working face is put forward, the application effect of new cuttable aluminum–plastic grouting pipe is explored, and a new anti-spalling technology of pre-grouting coal reinforcement before mining in working face is formed.

2. Materials and Methods

2.1. Failure Characteristics of Coal Wall Spalling in Working Face

The structural form and mechanical action of coal can be reflected by different coal wall spalling forms with large mining heights. Under the influence of different mining heights, bedding development degrees, and coal seam strengths, different forms of coal wall spalling failure will appear in large mining height working faces. The failure of coal wall in the working face is mainly caused by the combined action of roof pressure and gravity of the coal body, and the failure forms of coal wall mainly include tensile crack failure, bulging failure, and shear failure, as shown in Figure 1.

![Figure 1. Failure form of coal wall spalling: (a) tensile crack failure; (b) bulging failure; (c) shear failure.](image)

2.2. Advance Grouting Layered Flexible Reinforcement Technology

In order to control the coal spalling in the triangle area of the working face, the concept of the “artificial false roof” was proposed. The mechanism is to impact the roof or the upper part of the coal seam and use grouting pipe with certain rigidity and elongation to carry out grouting, thus forming an artificial roof that is relatively stable on the roof or upper part of the coal seam, thus realizing the reinforcement of super-long coal body [20]. Its advantage is that the spalling on the upper part of the coal seam roof can be well controlled by grouting [21], but the large amount of drilling direction control and the difficulty to transport in advance are its biggest shortcomings.

Therefore, based on the idea of the “artificial false roof”, the prevention technology of “fishbone” advanced pre-grouting flexible reinforcement of coal wall spalling is put forward. The principle is to open construction holes diagonally on the coal seam through the upper and lower air ducts and transport the grouting pipe to the coal seam, strengthening the friction angle and cohesion in the coal seam through grouting in advance, and forming a stable layer on the upper part of the thick coal body to prevent the coal body from spalling in the upper triangle. The advanced pre-grouting layout is shown in Figure 2.

![Figure 2. Layout of long-distance grouting: (a) simulated diagram; (b) plane graph.](image)
2.3. Materials

We compare the advantages and disadvantages of chemical slurry and double-liquid grouting. Chemical slurries have high strength but affect coal quality [22] and pre-grouting does not need the characteristics of early strength and high strength of chemical grout. Double-liquid slurry uses water glass to improve the solidification speed but affects the long-term strength [23], so it is not suitable either.

According to the method, pre-grouting is carried out before the mining of the working face, and because the grouting operation is far ahead of the working face, the slurry has a long solidification period, and the cement slurry is selected as the grouting material from the technical and economic point of view.

As the overrun pre-grouting requires the grouting pipe to penetrate to the bottom of the grouting hole to take into account the objective conditions of the coal mine, the grouting pipe must meet the conditions of easy cut off of the coal miner drum, good ductility and strength, good pressure resistance, low resistance to flow in the grouting pipe, good plasticity, and long service life [24,25].

Compared with the traditional support means anchor, although the traditional support means anchor can effectively overcome tensile stress and shear stress, its biggest problem is low elongation and high cost.

The aluminum–plastic composite pipe is a new type of pipe, which can integrate the advantages of plastic pipe and metal pipe. Its internal structure is composed of polyethylene, adhesives, aluminum, adhesives, and polyethylene [26]. The aluminum–plastic composite pipe has the advantages of light weight, low-flow resistance, good ductility, and easy cutting. The structure of the aluminum–plastic composite pipe is shown in Figure 3.

![Structure of the aluminum–plastic composite pipe](image)

**Figure 3.** Structure of the aluminum–plastic composite pipe: (a) front view; (b) sectional view.

Tensile pressure tests were carried out under different diameters of aluminum–plastic pipes. As shown in Figure 4, the average tensile strength of aluminum–plastic composite pipes with diameters of 12 mm, 16 mm, and 20 mm are 24.25 MPa, 20.85 MPa, and 22.02 MPa, and the average elongation after fracture is 26.13%, 34.73%, and 17.94%, respectively. Therefore, the aluminum–plastic composite pipe with a diameter of 16 mm is used as the grouting pipe.

2.4. Methods

The spalling mechanism is studied through the grouting strength test of broken coal and flexible pipe completed in the laboratory. In this experiment, specimens without flexible pipes, with one flexible pipe, with two flexible pipes, and with three flexible pipes were made, respectively. The manufacturing process of the test piece is as follows:

Step 1: Coal samples are crushed into coal blocks with particle sizes less than 10 mm, and the coal blocks are classified by a classification sieve.
Step 2: Make a coal sample test block with water:cement:coal ratio of 0.45:1:3 and size of 100 × 100 × 100 mm. After the test block is manufactured, it will be stored in an environment with a relative humidity greater than 95% for 28 days.

Step 3: After curing, carry out excavation with a length of 80 mm and a diameter of 10 mm, then prepare grouting fluid with the ratio of additive:cement:water = 1:9:2.7, and finally put the grouting pipe into the excavated grouting hole and add the grouting fluid to complete the test material. The simulation of the sample-making process and grouting hole position is shown in Figure 5.

![Figure 5. The process of making test pieces.](image)

After the specimen is made, the shear test, uniaxial compression test, and splitting tensile test with four different shear angles \(\alpha (40^\circ, 50^\circ, 60^\circ, \text{and} 70^\circ)\) are carried out on the press.

The influence of the number of grouting pipes on the compressive/tensile strength of the specimen is shown in Figure 6.

It can be seen from Figure 6 that grouting pipe can improve the uniaxial compressive strength of specimens, and with the increase of grouting pipe, the compressive strength of specimens also increases. The average compressive strength of the specimen is 16.11 MPa when it contains one grouting pipe, 18.36 MPa when it contains two grouting pipes, and 19.64 MPa when it contains three grouting pipes, which are increases of 14.10%, 17.38%, and 21.92%, respectively.
The tensile strength of coal samples without a grouting pipe is 2.56 MPa, with one grouting pipe is 2.93 MPa, with two grouting pipes is 3.17 MPa, and with three grouting pipes is 3.47 MPa. The specimen is shown in Figure 6.

Influence of grouting pipes on compression strength: (a) no grouting pipe; (b) one grouting pipe; (c) two grouting pipes; (d) three grouting pipes.

Figure 7. Influence of grouting pipes on compression strength: (a) no grouting pipe; (b) one grouting pipe; (c) two grouting pipes; (d) three grouting pipes.

Under uniaxial compression conditions, it can be seen from the comparison that the degree of crushing of coal samples without grouting pipe is serious, while that of coal samples with grouting pipe is light, and the degree of crushing of coal samples decreases linearly with the increase of the number of grouting pipes.

It can be seen from Figure 6 that the splitting tensile strength of coal samples is improved. The tensile strength of coal samples without a grouting pipe is 2.56 MPa, with one grouting pipe is 2.93 MPa, with two grouting pipes is 3.17 MPa, and with three grouting pipes is 3.22 MPa. Compared with coal samples without a grouting pipe, the tensile strength of coal samples with 1, 2, and 3 grouting pipes increased by 13.63%, 22.97%, and 24.91%, respectively.

Coal samples without a grouting pipe will be destroyed along the shear plane under shear conditions, and the broken coal samples will be separated, while coal samples containing a grouting pipe will not be separated after destruction.

Figure 6. Influence of grouting pipe quantity on specimen tensile and compressive strength.

The failure modes of compression/tension are shown in Figures 7 and 8.
The relationship between different grouting pipes, shear angles, and shear strengths is shown in Figure 9.

![Figure 9](image_url)

Figure 9. Relationship between different grouting pipes, shear angle, and shear strength: (a) different quantities of grouting pipe; (b) different shearing angles.

The internal friction and cohesion of the specimens with different grouting pipes are shown in Figure 10: 22.27° and 2.14 MPa for the specimen without a grouting pipe; 20.18° and 2.29 MPa for the specimen with one grouting pipe; 22.24° and 2.45 MPa for the specimen with two grouting pipes; 22.29° and 2.65 MPa for the specimen with three grouting pipes. The three groups of specimens with grouting pipes showed an increase in cohesion of 7.34%, 14.67%, and 14.68%, respectively, compared to the specimens without a grouting pipe.

![Figure 10](image_url)

Figure 10. Internal friction angle and cohesion of specimen containing grouting pipe.

The specimen is mainly made of coal sample mixed and cement, which has strong adhesion, but the perforation destroys the microstructure of the specimen itself, thus reducing the internal friction angle of the specimen. However, by increasing the number of grouting pipes, the coupling effect between grouting pipes and grouting fluid is enhanced, which makes the internal friction angle and cohesion of the specimen increase again. Therefore, the adhesive force of the specimen will increase with the increasing number of drilling holes, while the internal friction angle will decrease first and then increase.

3. Numerical Simulation of Flexible Reinforcement Technology

3.1. Simulation Content

It is planned to simulate the 14,030 working face of a mine, whose retrieval height is about 6 m. In the process of mining, the phenomenon of coal wall spalling often occurs. According to the geology and mining conditions of the working face, the FLAC3D
three-dimensional calculation model is established to simulate the influence of grouting hole spacing on coal wall displacement in different working conditions.

FLAC\textsuperscript{3D} mesoscopic parameter calibration is a complex process, at present, the “trial and error” method is mainly used, which first assigns a set of assumed mesoscopic parameters to the complete numerical model and performs simulation calculations: the macroscopic parameters obtained by simulation calculation were compared with the laboratory test results, and the micro parameters are adjusted continuously. When the simulation results are basically consistent with the experimental results, it is considered that the mesoscopic parameters are reasonable. Before debugging the mesoscopic parameters, the relationship between the mesoscopic parameters and the macroscopic mechanical parameters of rock should be clarified so that the mesoscopic parameters can be matched more quickly.

After a series of repeated laboratory tests, finally, we get a set that can reflect the rock’s macro-mechanical characteristics of the FLAC\textsuperscript{3D} mesoscopic parameters (Table 1) in order to evaluate the rationality and reliability of the mesoscopic parameters shown in Table 1. Because of the limitation of space, Figure 11 shows the most representative confining pressure. When the confining pressure is 3 Mpa, the simulated stress–strain curve of the coal seam is compared with that obtained in the test (the straight line is the test curve and the dotted line is the simulation curve). It can be seen from Figure 11 that the numerical simulation results are close to the laboratory test results, the peak stress is 56.9 Mpa and 53.6 Mpa, respectively, and the absolute error is 3.3 Mpa.

<table>
<thead>
<tr>
<th>Rock Stratum Name</th>
<th>Unit Weight (Kg/m\textsuperscript{3})</th>
<th>Bulk Modulus (GPa)</th>
<th>Shear Modulus (GPa)</th>
<th>Poisson Ratio</th>
<th>Tensile Strength (MPa)</th>
<th>Internal Friction Angle (°)</th>
<th>Cohesion (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy mudstone</td>
<td>2900</td>
<td>10.767</td>
<td>8.876</td>
<td>0.24</td>
<td>6.8</td>
<td>37</td>
<td>6.1</td>
</tr>
<tr>
<td>Coal seam</td>
<td>1600</td>
<td>1.786</td>
<td>1.304</td>
<td>0.35</td>
<td>1.3</td>
<td>31</td>
<td>1.2</td>
</tr>
<tr>
<td>Mudstone</td>
<td>2600</td>
<td>10.767</td>
<td>8.764</td>
<td>0.29</td>
<td>4.1</td>
<td>34</td>
<td>2.2</td>
</tr>
<tr>
<td>Medium grained sandstone</td>
<td>2700</td>
<td>6.653</td>
<td>5.75</td>
<td>0.28</td>
<td>2.2</td>
<td>35</td>
<td>2.5</td>
</tr>
<tr>
<td>Malmstone</td>
<td>2560</td>
<td>4.000</td>
<td>4.000</td>
<td>0.124</td>
<td>6.1</td>
<td>37</td>
<td>2.76</td>
</tr>
</tbody>
</table>

Figure 11. Comparison of stress–strain curves between laboratory test and simulation test.

To sum up, the strength values obtained by using the meso-parameters in Table 1 are close to the laboratory test values. It shows that the meso-parameters in Table 1 can reflect the macro-mechanical characteristics of the coal seam, roof, floor, and overlying strata, and can be used for subsequent corresponding simulation research.
3.2. Simulation Scenarios

- Single-row grouting hole reinforcement. The model of flexible reinforcement of coal seams with 2.0 m spacing and 1.5 m distance between the grouting holes and the roof is shown in Figure 12a. The model of flexible reinforcement of coal seams with 2.0 m spacing and 2.5 m distance between the grouting holes and the roof is shown in Figure 12b.

- Double-row grouting hole reinforcement. The model of flexible reinforcement of coal seams with 2.0 m spacing and 1.8 and 3.0 m distances between grouting holes from the roof is shown in Figure 13, and the model of flexible reinforcement of coal seam with 2.5 m spacing and 1.8 and 3.0 m distances between grouting holes from the roof is shown in Figure 13.

![Reinforcement model of single-row grouting pipe](image)

**Figure 12.** Reinforcement model of single-row grouting pipe: (a) 1.5 m from the roof; (b) 2.5 m from the roof.

![Reinforcement model of double-row grouting pipe](image)

**Figure 13.** Reinforcement model of double-row grouting pipe: (a) spacing of 2.0 m; (b) spacing of 2.5 m.

3.3. Calculation Model and Parameter Determination

According to the influence of mining on coal seam range, the model length \( l \) is shown in Formula (1):

\[
l \geq L_0 + 2 \times 30
\]  

(1)

Type, \( L_0 \): the first pressure interval, m.

The height \( h \) of the model is shown in Formula (2).

\[
h = h_d + M + h_c
\]  

(2)

Type, \( h_d \): roof thickness, the stope model is generally not fewer than 8 times the thickness of mining height are broken, \( M \): mining height is broken, generally take coal seam thickness, \( m \); \( h_c \): bottom plate thickness, m.

The model is 500 m long, 250 m wide, and 400 m high, with a design coal seam thickness of 6.0 m. The rock stratum used in numerical simulation is subject to the mining geological report of the 14,030 working face. Model constraints: impose constraints on one side of the model to limit horizontal movement, impose constraints on the model bed to limit vertical movement, and impose vertical load on the upper part of the model to simulate the weight of overlying strata. The quarry geometry model is shown in Figure 14.
ϕ is the angle of internal friction; ϕ value is 34.693 mm. Compared with no grouting hole, the maximum displacement change of 14,030 working face in a mine is 500 m and the average allowable weight is 2500 kg/m³, the vertical stress of the upper boundary of the model is q = -12.5 MPa. Considering the influence of tectonic geostress on coal seam, the horizontal stress and vertical stress of coal seam strike are equal, and the horizontal stress and vertical stress along coal seam inclination are equal.

Determination of calculation parameters. It can be seen from the indoor sampling test results that the specimen is destroyed after the load reaches the ultimate strength, and the residual strength of the specimen gradually decreases during the residual deformation after the peak value. This shows that the Mhor–Coulomb constitutive relation can be used to calculate the failure of rock mass (Formula (3)). This structural model is suitable for solving the problems of slope safety and stability and underground engineering excavation [27,28].

\[
f_s = \sigma_1 - \sigma_3 \frac{1 + \sin \varphi}{1 - \sin \varphi} - 2c \sqrt{\frac{1 + \sin \varphi}{1 - \sin \varphi}}
\]  

(3)

where \( \varphi \) is the angle of internal friction; \( c \) is the cohesion; \( \sigma_1 \) is the maximum principal stress.

When \( f_s \geq 0 \), shear failure will occur.

According to the field geological data and the experimental results of rock mechanics obtained from laboratory tests, considering the size effect of rock deformation and geological structure conditions, the rock mechanics parameters used in the simulation calculation are given, as shown in Table 1.

4. Results
4.1. Simulation Comparison of the Displacement of a Single Row of Grouting Pipes at Different Locations from the Top Plate

Under the same mining height, the spacing of the single row of holes is 2.0 m. Coal wall displacements from the grouting pipe to the roof were simulated at 1.5 m, 2.0 m, and 2.5 m, respectively, to determine the optimum distance of the grouting pipe from the roof, as shown in Figure 15.

As can be seen from Figure 15, the position with the largest compression displacement of the coal wall is the middle and upper parts. After flexible reinforcement by grouting through a single row of holes, the displacement of grouting holes is lower than that without grouting pipes. When the grouting hole is 1.5 m away from the top plate, the displacement value is 31.769 mm, and the maximum displacement change of the grouting hole is 3.408 mm. When the grouting hole is 2.0 m away from the roof, the displacement value is 33.308 mm, and the maximum displacement change is 2.866 m compared with that without a grouting hole. When the grouting hole is 2.5 m away from the roof, the displacement value is 34.693 mm. Compared with no grouting hole, the maximum displacement change

![Figure 14. Stope model: (a) three-dimensional model grid diagram; (b) model profile; (c) stope geometric model.](image-url)
is 2.806 mm. In contrast, the displacement change of grouting holes at different distances from the roof changes the most at 1.5 m. The best supporting distance is 1.5 m.

![FLAC3D 5.00](image)

(a) (b) (c) (d) (e)

**Figure 15.** Horizontal displacement of monitoring points at different distances from the roof: (a) no grouting pipe; (b) grouting pipe is 1.5 m away from the roof; (c) grouting pipe is 2.0 m away from the roof; (d) grouting pipe is 2.5 m away from the roof; (e) displacement line chart.

### 4.2. Comparison of Displacement Simulations with Different Spacing of Single-Row Grouting Holes

Under the same mining height, the displacement of the coal wall in the working face with grouting pipe spacing of 1.5 m, 2.0 m, and 2.5 m when the single-row grouting hole is 1.5 m away from the roof is simulated, and the optimal spacing is determined. The horizontal displacement of the working face is shown in **Figure 16**.
value is 33.308 mm, and the maximum displacement change is 2.866 m compared with that without a grouting hole. When the grouting hole is 2.5 m away from the roof, the displacement value is 34.693 mm. Compared with no grouting hole, the maximum displacement change is 2.806 mm. In contrast, the displacement change of grouting holes at different distances from the roof changes the most at 1.5 m. The best supporting distance is 1.5 m.

4.2. Comparison of Displacement Simulations with Different Spacing of Single-Row Grouting Holes

Under the same mining height, the displacement of the coal wall in the working face with grouting pipe spacing of 1.5 m, 2.0 m, and 2.5 m when the single-row grouting hole is 1.5 m away from the roof is simulated, and the optimal spacing is determined. The horizontal displacement of the working face is shown in Figure 16.

*Figure 16. Horizontal displacement diagram of monitoring points with different spacing of grouting pipes: (a) no grouting pipe; (b) grouting pipe spacing is 1.5 m; (c) grouting pipe spacing is 2.0 m; (d) grouting pipe spacing is 2.5 m; (e) displacement line chart.*

It can be seen from Figure 16 that the displacement of the coal wall of the working face with different spacings (spacing 1.5 m, spacing 2.0 m, and spacing 2.5 m) of the grouting pipe at the distance of 1.5 m from the roof is reduced compared with that of the working face without support, indicating that it is necessary to increase the strength of the coal wall of the working face through support. The displacement change is the largest at 2.0 m away from the roof, and the displacement without support is 36.174 mm. When the grouting pipe spacings are 1.5 m, 2.0 m, and 2.5 m, the displacement is 32.855 mm, 33.309 mm, and 34.760 mm, respectively, and the maximum displacement change is 3.319 mm, 2.865 mm, and 1.414 mm, respectively. The distance between grouting holes is 1.5 m and the displacement is the largest without support, indicating that its support effect is the best. Therefore, the grouting spacing of 1.5 m is the optimal spacing.

4.3. Simulation Comparison of the Displacement of the Double Row of Grouting Holes at Different Locations from the Top Plate

Under the same mining height, when the distance between two rows of grouting holes is 2.0 m, the distances between the grouting holes and the roof are 1.2 m and 3.0 m, 1.5 m and 3.0 m, and 1.8 m and 3.0 m, respectively. The displacement of the coal wall in the strengthened working face is simulated and the best distance is determined. Figure 16 shows the horizontal displacement of the coal wall in the working face strengthened by double-row grouting holes.
It can be seen from Figure 17 that the maximum compression displacement of the coal wall with large mining height is in the middle and upper parts. After the flexible reinforcement of the middle and upper part of the coal seam through double-row grouting pipes, the horizontal displacement of the grouting hole is lower than that of the control group. When the upper row of grouting holes is 1.2 m away from the roof and the lower row of grouting holes is 3.0 m away from the roof, the displacement value is 28.645 mm and the maximum displacement change is 3.851 mm. At this time, the displacement of the upper part of the coal seam is well controlled, but the displacement of the middle part cannot be controlled. When the upper row of grouting holes is 1.5 m away from the roof and the lower row of grouting holes is 3.0 m away from the roof, the displacement value is 31.207 mm and the maximum displacement change is 3.970 mm. Currently, the overall displacement of the coal seam is small. When the upper row of grouting holes is 2.5 m away from the roof and the lower row of grouting holes is 3.0 m away from the roof, the displacement value is 32.841 mm and the maximum variation of displacement is 3.359 mm. The displacement of the middle part of the coal seam is well controlled, but the displacement of the upper part is not controlled. In contrast, the displacement change of grouting pipe at different distances from the roof changes the most at 1.5 and 3.0 m, so it can be judged that the support at 1.5 and 3.0 m from the roof is the best.

Figure 17. Horizontal displacement of monitoring points with different distances between double-row grouting holes and roof: (a) no grouting pipe; (b) grouting pipe is 1.2 and 3 m away from the roof; (c) grouting pipe is 1.5 and 3 m away from the roof; (d) grouting pipe is 1.8 and 3 m away from the roof; (e) displacement line chart.
4.4. Comparison of Displacement Simulations with Different Spacing of Double-Row Grouting Holes

Under the same mining height, the displacement of the coal wall between the two rows of grouting holes and the working face when they are 1.5 and 3.0 m away from the roof is simulated, and the optimal spacing is determined. The horizontal displacement of the grouting pipe is shown in Figure 18.

It can be seen from Figure 18 that the coal wall displacement of the working face with different spacing of grouting pipes (1.5 m, 2.0 m, and 2.5 m) at the distance of 1.5 and 3.0 m from the roof is lower than that without reinforcement and single-row grouting hole reinforcement, indicating that it is necessary to comprehensively strengthen the working face. The displacement change is the largest at 2.5 m from the roof, and the displacement without support is 36.409 mm. When the grouting pipe spacings are 1.5 m, 2.0 m, and 2.5 m, the displacements are 32.834 mm, 33.455 mm, and 33.948 mm, respectively, and the maximum displacement changes are 3.657 mm, 2.945 mm, and 2.461 mm, respectively. The distance between grouting pipes is 1.5 m, and the displacement change is the largest,

![Figure 18](image_url)
indicating that its support effect is the best. Therefore, the grouting spacing of 1.5 m is the optimal spacing.

By simulating the different working conditions of the distance between the grouting holes and the roof and the distance between the grouting holes, it can be seen that when the optimal distance between the single row of grouting pipes is 1.5 m, the horizontal displacement of the working face is small, when the optimal distance between the double row of holes is 1.5 m, and when the distance between the single row of grouting pipes and the roof is 1.5 and 3.0 m, the horizontal displacement of the working face is the best.

5. UDEC Simulates the Effect of Preventing and Treating Patches

Through FLAC\textsuperscript{3D}, the displacement of the working face caused by grouting holes with different spacing and the distance between the grouting holes and the roof are analyzed. Because FLAC\textsuperscript{3D} is a static calculation software, it cannot simulate the whole process of coal wall spalling form, top failure, and collapse in the working face [29], so UDEC discrete element calculation simulation software is used to simulate the prevention effect of coal wall spalling in working face under different reinforcement positions with different distances between grouting holes and roof.

5.1. Calculation Model Building and Parameter Determination

1. Physical dimensions and boundary conditions of the simulation

   The establishment of the numerical model is based on the 14,030 working face of a certain mine. The length of the calculation model is 500 m, the height is 400 m, the mining depth of the simulated working face is 500 m, and the height of the model coal seam is 6.0 m. The model situation is shown in Figure 19.

2. Constitutive relationship and mechanical parameters of the model.

![Figure 19. Block model of primitive surrounding rock structure.](image)

According to the indoor sampling test results, when the load borne by the specimen reaches the ultimate strength, the specimen will be damaged, and the residual strength of the specimen will gradually decrease in the process of post-peak residual deformation. Therefore, it is planned to use the “Mohr Coulomb” constitutive model to calculate the failure of rock mass, which is suitable for solving the problems of slope safety and stability and underground engineering excavation. The model simulates the displacement change of the working face in the process of mining advancement and the relationship between the deformation and stress of the working face in the process of mining. It needs to consider the relationship of the plastic zone in the process of excavation, so the Mohr-Coulomb model is more suitable.

The attribute parameters required for numerical calculation are determined by the constitutive relation between the block and joint. See Table 2 for the mechanical parameters of the joint.
Table 2. Joint’s mechanical parameters.

<table>
<thead>
<tr>
<th>Rock Name</th>
<th>Normal Stiffness (Mpa)</th>
<th>Tangential Stiffness (Mpa)</th>
<th>Internal Friction Angle (°)</th>
<th>Cohesion (MPa)</th>
<th>Tensile Strength (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine-grained sandstone</td>
<td>3100</td>
<td>2670</td>
<td>30</td>
<td>1.4</td>
<td>7.3</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>3900</td>
<td>3500</td>
<td>37</td>
<td>6.1</td>
<td>6.8</td>
</tr>
<tr>
<td>Medium grained sandstone</td>
<td>2200</td>
<td>1700</td>
<td>35</td>
<td>1.4</td>
<td>7.3</td>
</tr>
<tr>
<td>Mudstone</td>
<td>1000</td>
<td>800</td>
<td>34</td>
<td>2.2</td>
<td>4.1</td>
</tr>
</tbody>
</table>

5.2. Prevention and Control Effect of Coal Wall Spalling under Different Supporting Conditions

The effect of reinforcement at different locations of the grout holes from the top slab is shown in Figure 20 and the displacement of reinforcement at different locations of the grout holes from the top slab is shown in Figure 21.

Figure 20. Reinforcement effect diagram of grouting hole at different positions: (a) without shoring; (b) 1.5 m from the roof; (c) 2.0 m from the roof; (d) 1.5 and 3 m from the roof.

Figure 21. Displacement diagram of grouting hole reinforcement at different positions: (a) without shoring; (b) 1.5 m from the roof; (c) 2.0 m from the roof; (d) 1.5 and 3 m from the roof.

It can be seen from Figures 20 and 21 that the failure modes and horizontal displacements of the coal wall in the working face are different at different positions from the grouting hole to the roof plate. Without a grouting pipe, the coal wall spalling position of the working face is located in the middle and upper parts of the working face. At this time, the displacement of the coal wall spalling of the working face is 1.5 m, the grouting hole is 1.5 m away from the roof, the coal wall is damaged in the lower part of the grouting pipe, and the horizontal displacement of the coal wall damage of the working face is 0.9 m. The grouting hole is 2.0 m away from the roof. After the grouting hole is reinforced with grout, the spalling of the coal wall face side is reduced, the displacement of the upper part of the grouting hole is reduced, the spalling of the face is below the middle of the coal seam, and the maximum failure depth is 0.7 m, which has achieved the effect of reinforcement. The grouting hole is 1.5 and 3 m away from the roof because the grouting pipe and grout are beneficial to improve the compressive strength of the coal wall and the cohesion of coal, currently, the strength of the coal wall in the working face increases and the slurry injection pipe plays a good supporting effect.
6. Discussion
6.1. Field Application of Flexible Reinforcement Technology

The 14,030 working face of a certain mine is the first working face with full-mining height at one time, and the average thickness of the mined coal seam is 6.4 m. The coal structure is mainly primary structural coal, and there is a small amount of structural coal near the fault. The tunneling length of the working face is 903.6 m, and the inclined width is 204.6 m.

In order to better control the spalling of coal wall and roof in the 14,030 high mining height working face of a mine, the cuttable aluminum–plastic composite pipe advanced pre-grouting reinforcement technology was designed to reinforce the coal wall of the working face. The grouting reinforcement parameters are as follows:

6.1.1. Angle of the Borehole

The load on the upper part of the coal wall of the working face is large, and the position of the wall is mainly concentrated in the middle and upper parts of the coal wall. The pillar-mounted drilling rig is used to drill the coal wall of the upper and lower air ducts, and the grouting hole is designed according to the actual elevation of the upper and lower air ducts. The opening position of the upper air duct is 1.6 m away from the top plate, and the opening position of the lower air duct is 2.5 m away from the top plate.

6.1.2. Borehole Length

The selected aluminum–plastic composite pipe has an inner diameter of 16 mm, and the grouting pipe can meet the requirements when lowered to 100 m, and the maximum thrust value at this time is 122 N. According to the actual situation, the drilling length is 85–100 m. Grouting hole excavation is shown in Figure 19.

6.1.3. Sealing Length

The hole sealing bag is used for hole sealing, and the hole sealing length is 3–4 m. Due to the development of coal interstices around the roadway, slurry leakage easily occurs in the grouting process, so double-liquid grouting is adopted at the initial stage of grouting. As shown in Figure 22. When the slurry flows out of the exhaust pipe, the choke valve of the exhaust pipe is closed, and the slurry diffuses to the crack and begins to solidify at the same time, thus achieving the effect of sealing the crack.

6.1.4. Grouting Pressure and Grouting Volume

The grouting pressure is used to overcome the cohesion of the slurry itself and the flow resistance of the hole fissure surface with the medium in the flow process. Since the grouting project needs to be carried out in the mining roadway, and the upper and lower air ducts need to be transported and constructed normally during the grouting period, the grouting pump used is a pneumatic grouting pump with a maximum displacement of 40 L/min.

![Figure 22](image-url)

Figure 22. Application of flexible reinforcement: (a) grouting hole digging; (b) aluminum–plastic pipe installation; (c) grouting hole sealing; (d) under the shaft grouting.
According to experience, the design grouting pressure is 10 MPa. According to statistics, the average grouting volume of grouting holes is about 5 t, with a maximum of 9.5 t.

6.2. Application Effects

The tensile strength and shear strength of the coal body itself are low before strengthening the coal wall in a large mining height working face of a mine. Through the analysis of the peeping results of the gateway roof drilling on the working face, the integrity of the roof is greatly affected by the mining movement.

According to the advancing speed of the working face, the pre-grouting before the mining of the working face shall be carried out 10–14 days in advance. After on-site grouting, the drilling shall be carried out along the design angle of the grouting hole between the two grouting holes. The distance between the detection drilling hole and the grouting holes on both sides is 1.0 m and the length is 30 m. After the completion of drilling construction, clear the hole in time and peep the coal wall. The comparison of borehole peeping before and after grouting is shown in Figure 23.

![Comparison of drilling views before and after grouting](image)

**Figure 23.** Comparison of drilling views before and after grouting: (a) before grouting; (b) after grouting.

Because the aluminum–plastic composite pipe has good elongation and strong tensile strength, there is no un-sudden slip in the process of loading the coal body, and because the aluminum–plastic composite pipe has an obvious deformation process and cracking damage so no large area of the overall collapse of the slip will occur.

The aluminum–plastic composite pipe and the grouting fluid work together to form a stone body, which can improve the internal friction angle of the coal body and its own strength, and thus play a better role in preventing spalling. A comparison of coal wall spalling before and after reinforcement is shown in Figure 24.

![Comparison of coal wall conditions before and after reinforcement](image)

**Figure 24.** Comparison of coal wall conditions before and after reinforcement.

During the advancing of the working face, the spalling of the coal wall is well controlled, and only a small amount of coal spalling exists, which does not affect the mining, ensures the safety of personnel and equipment in the stope, saves a lot of time for mining in the working face, and the daily output of the working face exceeds 10,000 tons.

7. Conclusions

(1) In order to make the mining face with a large mining height efficient and safe, the existing traditional measures for preventing spalling of the coal wall in large mining height face in China are passive measures taken after spalling, so the supporting effect
is not good. Therefore, a layered flexible reinforcement technology with advanced pre-grouting is proposed. Pre-grouting flexible reinforcement is an advanced, economical, and safe supporting measure against spalling, which can effectively control spalling and roof fall of the coal wall.

(2) An aluminum–plastic composite pipe has the advantages of good ductility, good pressure resistance, high tensile strength, and low price. Through the strength test of the “grouting + flexible pipe” sample, the deformation and strength of coal samples with different numbers and diameters were studied. The optimal distance of horizontal displacement of single-row grouting pipe is 1.5 m, and the optimal distance from the roof is 2.0 m; the optimal distance of horizontal displacement of double-row grouting pipe is 1.5 m, and the optimal distance from the top plate is 1.5 m and 3.0 m.

(3) Through the practical field application, it is known that by supporting the coal wall of the working face, an unexpected collapse will not occur in the process of loading the coal body, and it has obvious cracking damage, which will not lead to large-area integrity collapse, thus achieving a good anti-spalling effect.

Author Contributions: Conceptualization, H.J. and W.Y.; methodology, H.J.; software, W.Y.; validation, X.C., L.Y. and Z.L.; formal analysis, L.Y.; investigation, W.Y.; resources, H.J.; data curation, X.C.; writing—original draft preparation, W.Y.; writing—review and editing, H.J.; visualization, Z.L.; supervision, H.J.; project administration, X.C.; funding acquisition, H.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The Henan Polytechnic University Science Fund for Distinguished Young Scholars, grant number No. J2020-3; The Key Science and the Technology Program of Henan Province, grant number No. 212102310107 and No. 212102310602; The China Postdoctoral Science Foundation, grant number No. 2020M672226.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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