INTRODUCTION

Chinese coal industry has gone through a serious recession since 2012 due in large part to the excessive coal supply.\(^1\)\(^-\)\(^3\) China has then started the overcapacity cutting operations including shutdown of small collieries and reorganization of large coal enterprises. A total of 14 major coal bases were identified; each provides over 100 million tons of coal, and together they contribute over 95% of the national total production. Of those, Shendong, Shanbei, Huanglong, and Xinjiang coal bases are located in the north and west part of China, where extra thick coal seams of 6-9 m are widely observed. Such seams are typically flat and shallow, above which massive and strong conglomerate channels are occurred. Luxi, Jizhong, Henan and Lianghuai in the central and east part of China typically find the inclined and weak coal seams of 3-5 m with deep depth, geological structural disturbances, and weak roof and floor. The seams are recovered using the full-seam single-pass longwall system at the extraordinarily high mining height, deeply inclined angle, or extremely weak seam/roof, which is termed the difficult mining and geological conditions in this paper.

Longwall face falls have been recognized as one of the most difficult ground control problems in mining thick coal seams in China especially under difficult geological conditions. This paper has proposed a new flexible bolting and grouting technology for face support. The flexible support method includes face support using flexible coir ropes and face grouting with cement and accelerator mixtures. Numerical and laboratory studies of pullout tests are performed to further improve the flexible support performance including optimization of boreholes and flexible bolts diameters, and selection of grouting materials. The results show that (a) The optimized rope-borehole diameter ratio is around 0.5 to ensure the best face reinforcement; (b) The grouting material (a mixture of ultrafine cement, mineral powder and sodium silicate) shows advantages of low cost, effective waste disposal, reduced setting time, and good pullout limit force and is recommended for industrial application with sodium silicate at a proportion of 10% by weight and mineral powder at 30%. The application of the new flexible bolting and grouting method in Chenmanzhuang mine shows improved face stability and reduced capital cost.

KEYWORDS
face fall, face reinforcement, flexible bolting and grouting technology, optimization, pullout test
The face fall problem is significantly increased under the abovementioned difficult geological conditions, typically associated with other ground control problems such as immediate roof cavity, aggressive periodic weightings, high pressures on shield legs, or a massive impact loading on support units leading to an iron-bound shield at full closure of the hydraulic legs.4-12 Figure 1 shows the face failures in Chenmanzhuang mine, Luxi coal base (Shandong Province). The face is operated at an inclination angle of 40°. The shield front plates are designed to attach to the face vertically and provide additional horizontal confinement. The plates at this face, however, extend forward and fail to provide support to the face, indicating a potential roof cavity and increased tip-to-face distance.

The face failures can be divided into structural failure and functional failure.13-16 Stress normally exceeds peak coal strength in abutment pressure zones around the longwall face. The coal mass around abutment zones may fracture or yield; it may not fall since it is relatively confined laterally and is unable to deform. When the shearer cuts to mine the coal face, the fresh coal exposes and loses the confinement. The face protection plate in the front edge of roof supports increases confinement and is therefore utilized in field practice to improve stability of the face.

Upon the failure of the coal and rock mass in the abutment pressure zones, the maximum front abutment stress would shift forward ahead of the face into more competent rock and coal mass. The local failure of the coal mass may not however lead to face falls on a longwall face. The coal may remain relatively stable and maintain its integrity for a short period of time without affecting mining operations until next mining cycle. This is considered a “structural failure” of the longwall face. “Functional failure” on the other hand refers to the state where face falls occur, and the production and safety of miners is affected. Structural failure may extend 0.5-2 m ahead of the longwall face, while extension of functional failure should be less than or equal to that of the structural failure. The purpose of face failure control is to reduce the likelihood of structural failure and prevent the occurrence of functional failure.

Since the face failures were typically observed as soft coal sliding from the longwall face, the face fall mechanism was mostly analyzed as a slope stability problem using the limit equilibrium approach, including the safety margin approach, Bishop method, Janbu method, and 3-D wedge stability model.17-19 Hard coal blocks were also observed splitting from the face and the theorem of limit analysis and Ritz method were therefore applied to assess the hard coal face failure mechanism.15,20 Parametric analysis has been performed based on the theoretical models to assess the influence of seam height, depth of cover, seam inclination, coal mechanical properties, and shield performance on face stability.21,22 In addition, a number of numerical and physical modeling studies of longwall face failure have been performed to reproduce the progressive development of face collapse with face advance.14,23-26 Important factors such as gob stiffness, shield stiffness, and shield loading characteristics were also included. These studies have provided broad-based observations on how these factors affect face failure.

Engineering solutions have been proposed to control face falls since the introduction of longwall face. Efforts to enhance face stability can be classified as follows: (a) optimizing mining operations to minimize impact of face collapse and (b) improving the coal face strength.13 The first group includes solutions such as moving the shield soon after mining to apply pressure to the roof, increasing shield load capacity and gob stiffness to reduce stress ahead of the coal face, improving the face advance rate, reducing the cutting depth of shearer, decreasing the mining height or face width, and mining along the rise in inclined seams. While face fall control techniques such as the face protection plate, coal face grouting and face support using wooden bolts fall into the latter one. The grouting materials include superfine cement, polyurethanes, resins and other chemical materials. Despite these practices, longwall faces continue to experience face failures and falls. Therefore, it is important to further improve the engineering solutions to control face collapse.

The primary goals of this paper are to (a) propose a new face flexible bolting and grouting technique for face fall control and (b) optimize the bolting and grouting parameters to enhance face stability and reduce the cost. Goals of this research are achieved by pullout tests of flexible bolt
using numerical and experimental approaches for assessing the influence of selected variables/parameters on face stability.

2 | FACE FLEXIBLE BOLTING AND GROUTING METHOD

The traditional wooden bolt provides only limited local support to the face. It also accommodates less horizontal displacement of the face. The chemical material MARITHON for face grouting, on the other hand, is way too expensive. The first author of this paper has proposed a face flexible bolting and grouting method for face fall control using flexible bolts and grouting materials. The coir ropes show good percent elongation at tension and are therefore used as the flexible bolts, while the cost-effective cement grout can be used as the grouting material. Figure 2 provides a schematic of the face flexible bolting and grouting method. For easy operation, a semicircular grouting steel pipe is used to install the flexible coir rope to the drillhole. The installation procedures include the following: (a) Placement of the flexible bolts in boreholes on face using the semicircular steel pipe; (b) Seal of the drillhole for face grouting preparation; and (c) Injection of grouting materials into the drillhole.

The fully grouted flexible bolt is able to accommodate the large deformation of the solid coal face. It not only increases the overall strength of coal face (by bolting and grouting) so as to reduce the likelihood of structural failure, but also improves the ductility and deformation capacity of the seam and prevents the occurrence of functional failure. When face fall occurs at extreme conditions, the flexible bolts function to hold the coal blocks and prevent from falling into the open face area to miners and equipment. The proposed face flexible bolting method has been used in several mines with enhanced face stability. The flexible bolting method has been used in several mines with enhanced face stability. The flexible bolting method is also cost-effective as compared to other bolting materials such as wooden or fiberglass bolts. However, it is necessary to further optimize the flexible bolting operations to improve the application for better face control and for seams under difficult geological conditions. The influencing factors such as diameters of boreholes and coir ropes, and selection of grouting materials are included in this study.

3 | NUMERICAL MODELING OF FLEXIBLE SUPPORT OPTIMIZATION

3.1 | Model development

Face 3402 of Chenmanzhuang mine is modeled in this research using FLAC3D. Figure 3 shows the lithological sequence of the numerical model, including a typical 2 m immediate roof, 4 m coal seam and 2 m immediate floor. The overall dimensions of the 3D model are 10 m long, 10 m wide, and 8 m high, with roller boundaries applied to the six sides of the model. Premining stresses of 7 MPa (X-direction), 7 MPa (Z-direction) are applied to the model.

The face in the model is reinforced with a 5-m long coir rope and grouted with the superfine cement (see Figure 3). The 8-node hexahedral element is used for modeling the coal seam, while cable element is used for the flexible bolts. Pullout test is performed by applying a constant velocity to the free end of the flexible bolt. The axial stiffness of the flexible bolt is described in Equation 1 shown as.

$$k = \frac{AE}{L}$$

FIGURE 2 | Face flexible bolting and grouting method: A, Schematic. B, Placement of coir rope on the semicircular grouting steel pipe for installing the flexible bolt to the borehole

FIGURE 3 | Numerical model used to evaluate the reinforcing effect of the face flexible bolting and grouting approach
where $A$ is the cross-sectional area of the coir rope; $E$ is the elastic modulus; $L$ is length of the coir rope. The interaction between the coir rope, grouting material, and solid coal is described using the spring–slider model shown in Figure 4. The shear stiffness of the grouting material per unit thickness is given as

$$K_g = \frac{2G\pi}{\ln\left(1 + \frac{2r}{d}\right)}$$  \hspace{1cm} (2)

where $G$ is the shear modulus of the grouting material; $t$ is the thickness of the annulus grouting material from the coir rope to solid coal; $d$ is the diameter of the coir rope.

Mohr–Coulomb failure criterion is used for analysis in this study. The material is assumed as elastic–perfectly plastic. The structural elements are allowed to deform and yield along the axial direction. The interface between grouting materials and surrounding rocks may experience both shear movement and slippage. Table 1 shows the rock mass engineering properties for different lithologies and the flexible bolting system in modeling. Mechanical parameters for roof, coal, and floor are obtained from laboratory tests on cored samples, and important parameters of coir ropes are selected from the national standard. The average tensile strength and percent elongation of the coir ropes at different diameters are obtained by performing tensile tests and are given in Table 2. The grouting material used in the numerical model is superfine cement.

The diameters of boreholes and coir ropes may have an important impact on face reinforcement and should be optimized to improve the face support in the open face area. A dimensionless factor is developed to assess the proper size of the boreholes and flexible bolts, which is defined as the ratio of borehole diameter to coir rope diameter given in Equation 3.
where $r$ is the rope-borehole ratio; $d$ is the diameter of the coir rope; $D$ is the diameter of the borehole.

### 3.2 | Performance of the flexible bolts

The performance of face flexible reinforcement technology at different diameters of boreholes and coir ropes is included in this study. Figure 5 gives the axial load–displacement and the yielded state of the coir ropes at different stages of the pullout test. Note that the diameters of the borehole and coir rope in this model are 42 and 24 mm, respectively, corresponding to a rope-borehole ratio of 0.57. The axial load and displacement are relatively small at the initial stage (Stage 400). The grouting materials are in elastic, and no slippage or failure along the interface is observed. The axial load of the flexible bolt and the volume of yielding zones of grouting materials increase with the displacement. When the calculation step reaches 3300, the displacement of the flexible bolt at the free end is 100 mm, while the length of the yielding grout reaches 2.5 m. The maximum axial load of the bolt reaches 119 kN at the 6400th calculation. Failure was observed along the full length of the bolt. The axial load of the flexible bolt stabilizes at approximately 120 kN due to the mechanical assumption of the CABLE structural element in FLAC, which is also the shear force limit of the grouting materials.

### 3.3 | Optimization of rope-borehole ratio

The optimization of face flexible bolting and grouting method is studied by changing the rope-borehole ratios. Figure 6A shows the axial load–displacement of a 24 mm diameter flexible bolt at different borehole diameters (or equivalently rope-bore ratios). The axial load increases with the displacement of the flexible bolt. The flexible bolt with larger rope-borehole ratio shows a greater axial load at the same displacement, but a smaller displacement when the limit tensile strength of the coir ropes is reached. Figure 8 shows the axial load distribution along the full length of coir ropes with different diameters at a borehole diameter of 42 mm. The axial load maximizes at the free end of the coir rope and decreases along the coir rope inside the solid coal. It is also observed that the axial load increases with the rope diameter (or the rope-borehole ratio). The 24 mm diameter coir rope with a rope-borehole ratio of 0.57 shows the maximum tensile load of 30.2 kN, compared to 5.5 kN for the 14 mm diameter rope with a rope-borehole ratio of 0.33.

Figure 7 plots the development of plastic zone of the grouting materials at different borehole diameters. The rope-borehole ratio is also shown in the figure. The bolt diameter is 24 mm in this model. A negative relationship is observed between the plastic zone and rope-borehole ratio. As the borehole diameter increases, the failure zone of the grout decreases until it reaches 0. Considering the consumption and stability of the grouting materials, the borehole diameters are suggested at 46 mm, corresponding to a rope-borehole ratio of 0.52. Similar models are developed to investigate the optimization of the borehole dimensions for the 28- and 32-mm bolts. The results show that the best rope-borehole ratios are found at 0.48 for both models.

### 4 | EXPERIMENTAL STUDY OF FLEXIBLE SUPPORT OPTIMIZATION

To verify the applicability and credibility of the numerical study, the authors have conducted the experimental pullout tests by pulling the coir ropes from the coal-like physical samples at different borehole and rope diameters (rope-borehole ratios) and recording the pullout limit load. Meanwhile, the proper selection of grouting materials is also included in the experimental study. This is because the commonly used grouting material MARITHON in the field is about 25 000-32 000 RMB per ton, and the demand for MARITHON is large. Coal mines have to spend a huge amount capital on grouting materials. Therefore, it is necessary to find a low-cost alternative grout to further improve its application in the industry. In this study, the authors have compared the reinforcement performance of three selected grouting materials, that is, the ultrafine cement grout (Grout 1), the mixture of ultrafine cement and sodium silicate (Grout 2), and the
mixture of ultrafine cement, mineral powder, and sodium silicate grout (Grout 3), to find out a proper grouting material for field practice.

4.1 Sample preparation and experiment design

The materials used in this research for construction of the coal-like physical samples are a mixture of coal ash, cement and water with the proportion of 1:1:2 by weight. The solid materials are fully mixed before the addition of water to ensure an overall isotropy and homogeneity. The over size of the coal-like samples is 200 mm long, 200 mm wide, and 100 mm thick. The sample is cured at the room temperature for 28 days before the 100-mm long borehole drilled through the sample in thickness. Coir ropes are placed in the sample boreholes and are injected with grouting materials.

The authors have developed two groups of pullout tests. The first group of experiment compares the reinforcement of the three abovementioned grouts (Figure 8A). The second group studies the reinforcement of flexible support under different boreholes and coir ropes diameters (rope-borehole ratio). Two borehole diameters at 26 mm and 32 mm are selected in this study, which is commonly used in the field, while the rope diameters are increasing from 8 mm to 24 mm at an interval of 2 mm (Figure 8). The pullout tests are performed 4 h after grouting using the loading machine (Figure 9). The pullout limit force, setting time of the grouts, and load–displacement of the flexible bolts are obtained for assessing the performance of grouting materials and optimization of rope-borehole ratio.

4.2 Selection of grouting materials

4.2.1 Grout 1: ultrafine cement grout

Ultrafine cement grout is popular in the industry since the material is widely available and cost-effective. The grout also shows good strength after setting. One of the disadvantages, however, is that Grout 1 takes a long time to set. Cement accelerator is normally added to Grout 1 to reduce the setting time. Figure 10 shows the pullout force limit and setting time of Grout 1 at different amount of cement accelerator added to Grout 1 by weight percent. The limit force is slightly larger than 0.5 kN and maximizes at 0.52 kN, indicating that the cement accelerator has little to none impact on the limit force. By contrast, the setting time decreases rapidly with the increase of accelerator. The setting time is <400 s when the amount of accelerator is 5%, which is considered adequate for the engineering application.

4.2.2 Grout 2: ultrafine cement–sodium silicate grout mixture

The sodium silicate can also be used as an accelerator to speed up the setting time and increase the early strength and mechanical properties of the grouting material. Figure 11 gives the limit force and setting time of Grout 2 at various amount of added sodium silicate. An overall negative relationship is observed between the limit force and sodium silicate. The maximum pullout load is 4.2 kN when the...
sodium silicate is 10%, which is about eight times the Grout 1. However, it decreases rapidly with the increase of sodium silicate. The decrease rate slows down when the sodium silicate is 30%-70%, followed by another rapid drop in limit force when the amount of sodium silicate is over 70%. On the other hand, when the sodium silicate is <70%, the setting time is <300 s and averages at 94 s. This is significantly less than the setting time for Grout 1. A further increase in sodium silicate sees the significant increase of setting time. It also should be noted that the ultrafine cement and sodium silicate of Grout 2 should be injected separately.

**FIGURE 8** Final view of the samples with coir ropes after grouting: A, samples with the 32 mm diameter borehole and different size of coir ropes. B, samples with different grouting materials

**FIGURE 9** Setup of the pullout test

**FIGURE 10** Pullout force and setting time of Grout 1

4.2.3 | Grout 3: ultrafine cement–mineral powder–sodium silicate grout mixture

Mineral powders can also be used in the surrounding rock grouting in the open face area and coal mine entries. The mineral powders are considered green grouting materials because of the efficient waste disposal and reduced cost. The material is added to Grout 3 while maintaining the weight percent of sodium silicate at 10%. Limit force and setting time of Grout 3 are shown in Figure 12. The limit force is about 1.6 kN when the mineral powder is <30%. It decreases rapidly with the
increase of mineral powders. On the other hand, the setting time of Grout 3 is <300 s and averages at 155 s when the mineral powder is <70%. The average setting time is larger than Grout 2, indicating that mineral powders function as a setting retarder. The cost of the proposed Grout 3 is reduced to 1700 RMB per ton. For the cost considerations, Grout 3 is selected as the grouting material for filed application with the sodium silicate at a proportion of 10% and mineral powder at 30% by weight.

4.3 Influence of rope-borehole ratio

The load–deformation curves at different rope-diameter ratios for the 26-mm diameter borehole samples are shown in Figure 13. The 26-mm borehole samples show relatively nonlinear increase of pullout load with the extension of flexible bolts at the beginning of pullout test. The peak pullout load is 0.7-1.3 kN at the deformation of 10-45 mm. The pullout force then drops dramatically after the peak, indicating the failure of the bonding interface. Compared to the immediate drop (a sudden failure) for the samples with rope-borehole ratios larger than 60% (Figure 13 right), the decline is less sharp for samples at less rope-borehole ratios (Figure 13 left). It is also noted that the grouting materials have not failed completely, since a residual load is reached at further extension of coir ropes. This is an important mechanical behavior for the flexible and grouting face support method because the flexible bolt and grout still provide confinement to the face and protect from the occurrence of functional failure. The residual load is about 0.4-0.8 kN. At the cease of pullout test, the maximum deformation stops at 65 mm, indicating that the flexible and grouting face support method may accommodate a large deformation of the longwall face.

Figure 14 gives the load–deformation curves at different rope-diameter ratios for the 32-mm borehole sample. Before the pullout force reaches the limit, it increases steadily and linearly with the extension of coir ropes. The limit load is about 0.5-1.4 kN for all the samples, corresponding to the deformation of 20-40 mm. A significant and sudden drop in the pullout load is then observed after the peak, and the residual load is about 0.1-0.7 kN.

The relationship between the limit force and rope-borehole ratio is given in Figure 15. Generally, the limit force first increases then decreases with the rope-borehole ratio, which agrees with the numerical modeling results. The rope-borehole ratio represents the amount of grout materials injected between the interface of coir rope and solid coal. The decrease of the limit force might due to the fact that the amount of grout materials reduces with the increase of rope-borehole ratio. A proper rope-borehole ratio is approximately between 0.45-0.70, which produces the largest limit force of 1.2-1.4 kN. At the similar
rope-borehole ratio, the 32-mm borehole samples show slightly larger limit force than the 26-mm counterparts, indicating that a larger borehole may improve the confinement to the face.

5 | FIELD APPLICATION

Face fall of longwall has long been recognized a ground control problem in Chenmanzhuang coal mine, Shandong Province, Luxi coal base. The 3.5 m thick Face 3402 is working at a very difficult and complex geological condition at an inclination angle of 30° and a cover depth of 1000-1200 m. The mudstone immediate roof is weak and soft, and the roof cavity is frequently observed in the tip-to-face area, which further increases the risk of face fall. The face flexible bolting and grouting technique is used in this coal mine to control face fall. Since the face failure is severe and large coal blocks are observed falling from the coal face to the open face area, the borehole diameter drilled on the coal face wall is determined as 42 mm, and the coir rope diameter is selected as 24 mm based on the numerical and experimental studies (rope-borehole ratio: 0.57). The borehole is 5 m deep into the solid coal face, 2 m above the floor, and at a spacing of 4.5 m. Boreholes are drilling at an angle of 30-45° toward the immediate roof direction above the bed layer. Table 3 lists the important parameters of the boreholes on longwall face.

After the creation of boreholes on the longwall face, the semicircular grouting steel pipe is used for the easy setup of the coir ropes in the drillholes. The flexible bolt is installed by placing on the semicircular steel pipe, through which the grouting materials are injected to the solid coal face (see Figure 2B). The ultrafine cement–mineral powder–sodium silicate mixture (Grout 3) is used as the grouting material based on the above experiment. The free end of the flexible bolt is properly sealed to ensure the face reinforcement performance. The semicircular steel pipe is recycled after grouting. Figure 16 shows the face performance after the face support using the flexible bolting and grouting method. Compared with the poor face stability with uneven solid coal wall before face support (Figure 1), the current longwall face is intact and no face fall is observed. The stability of immediate roof ahead of shield tip is also better off. Longwall face advances without significant face fall problem.

6 | SUMMARY AND CONCLUSIONS

This paper introduces a new flexible bolting and grouting method for face support. The coir rope is selected as the

| Diameter (cm) | Depth (m) | Spacing (m) | Distance from floor (m) | Angle with relation to bed layer (°) |
|---------------|-----------|-------------|-------------------------|---------------------------------|
| 42            | 5         | 4.5         | 2                       | 30-45                           |

TABLE 3 Important parameters of boreholes on face
flexible bolt, and the mixture of cement with accelerator is used as the grouting material. The semicircular steel pipe is utilized for bolt installation and face grouting. Pullout tests on face flexible bolting and grouting technique are performed using FLAC3D and laboratory tests. The proper rope-borehole ratio and proportion of grouting materials are the selected parameters in this work for optimization of the new face support method. The face flexible bolting and grouting method with recommended parameters is practiced at the studied mine site with difficult geological conditions. Important findings are listed below:

1. The optimization of the rope-borehole ratio is studied by the pullout test using both the numerical and experimental approaches. The numerical modeling shows that a larger rope-borehole ratio may increase not only the axial load of the flexible bolt but also the failure zone of the grout. A favorable rope-borehole ratio is about 0.5. The laboratory pullout tests on coal-like samples confirm that a proper rope-borehole ratio is approximately between 0.45 and 0.70 for producing a larger limit pullout force. Increase of borehole diameters while maintaining the optimized rope-borehole ratio may also improve the axial force.

2. Three grouting materials including the ultrafine cement grout (Grout 1), the mixture of ultrafine cement and sodium silicate (Grout 2), and the mixture of ultrafine cement, mineral powder, and sodium silicate (Grout 3) are selected to investigate the performance on face reinforcement from experimental pullout tests on the coal-like samples. The limit force of Grout 1 after setting is 0.5 kN. Grout 2 shows the maximum pullout force of 4.2 kN when the sodium silicate is 10%. Grout 3 has the limit force of 1.6 kN when the mineral powders are <30%. For the cost considerations, Grout 3 is selected as the grouting material for engineering application while maintaining the sodium silicate at the proportion of 10% by weight, and mineral powder at 30%.

3. The new flexible bolting and grouting method is practiced in Chenmanzhuang coal mine for face fall control. The diameters of the borehole and coir rope are determined as 42 mm and 24 mm from the numerical and experimental studies. Grout 3 is injected to the boreholes on the longwall. The face flexible bolting and grouting method not only increases the face stability but also reduces the capital cost.

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