Permeability enhancement mechanism of sand-carrying hydraulic fracturing in deep mining: A case study of uncovering coal in cross-cut

Yin Shuaifeng1 | Ma Haifeng2 | Cheng Zhiheng1 | Zou Quanle3 | Li Yingming2 | Jia Housheng4 | Zhang Kexue1

1Safety Engineering Center, North China University of Science and Technology, Beijing, China
2Faculty of Energy and Safety Engineering, Key Laboratory of Safety and High-efficiency Coal Mining, Anhui University of Science and Technology, Huainan, China
3State Key Laboratory of Coal Mine Disaster Dynamics and Control, College of Resources and Environmental Science, Chongqing University, Chongqing, China
4School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, China

Abstract
Coal and gas outburst disasters are prone to occur within rock cross-cut coal uncovering in deep underground coal mines. To reduce the risk of coal and gas burst under rock cross-cut coal uncovering, a technique of permeability enhancement using hydraulic fracturing sand-carrying is proposed. Field test was conducted using HF sand-carrying approach, and the effect of permeability enhancement was investigated. The results show that the evolution of cracks has been subjected three stages: energy slowly increasing and crack initiation, damage localization of coal seam and gradually failure, and crack instability expansion and formation of a complex fracture network system. In addition, it is found that “water-sand” type injection of high-pressure fluid carried sand into HF cracks, which creates a support force on crack surface and prevents crack closure. A fully developed fracture network system with high flow conductivity capacity is created and thus increases gas permeability largely. Furthermore, a clearly increasing trend associated with the HF sand-carrying is found for the treated coal seam area. The permeability coefficient is about 21.5-30.5 times higher than that from the raw coal seam. A good prevention effect of coal and gas outburst is achieved using HF sand-carrying method.

KEYWORDS
coal and gas outburst, deep mining, hydraulic fracturing, permeability enhancement, uncovering coal
1 | INTRODUCTION

Coal and gas outburst is an extremely complicated dynamic instability phenomenon in underground mines, which is a combined effect of many factors such as in situ stress, gas pressure, and strength of coal rock masses.\(^1\)-\(^7\) Coal and gas outburst threatens the production safety seriously in underground coal mines. It has proven that high risk and large damage strength of coal and gas outburst are closely related to the condition of rock cross-cut coal uncovering, which can trigger the coal and gas outburst due to distinct features within the rock cross-cut uncovering coal area such as high gradient of stress and gas pressure, large quantity of gas sources from coal seams, large span of rock cross-cut, and high stress concentration. Therefore, it is necessary to take preconditioning techniques for gas burst-prone coal seam to reduce or eliminate the risk of outburst potential ahead of coal uncovering in the rock cross-cut.\(^8\)-\(^12\) Nowadays, many techniques have been developed to address the coal and gas burst issues, for instance, pressure relief method of protective layer mining, water injection, gas predrainage, hydraulic slotting, and hydraulic fracturing.\(^13\)-\(^18\)

Hydraulic fracturing (HF) is an effective method for improving the permeability in oil and gas reservoirs; meanwhile, it is also used for the coal bed methane (CBM) development due to the merits in CBM resource exploitation, coal and gas burst disaster, and emission reduction. Many studies have been conducted referring to topics of coal and gas outburst triggered by rock cross-cut coal uncovering and permeability enhancement using hydraulic fracturing technique. On the basis of hydraulic fracturing, Lin et al\(^19\) proposed a permeability enhancement technique associated with pressure relief using a high-pressure pulse hydraulic fracturing method. They studied the propagation law of fluctuating pressure in the fracturing filed and investigated effect of pressure relief on the permeability enhancement. Bai et al\(^20\) have investigated the tempo-spatial effects of hydraulic fracturing by drilling through underground coal mine strata on desorption characteristics. Zhai et al\(^21\) proposed a method of pulse hydraulic fracturing for permeability enhancement of coal seam, and they conducted a series of experimental tests under various frequencies and pressures. They found that alternating stress state is formed at end tip of fractures due to the intensive pressure of pulse water. A repeated action of “compression-expansion-compression” is formed within the coal masses, which ultimately assist to generate a complex fracture network system. In addition, for issue of coal and gas outburst may be triggered by coal recovering at rock cross-cut area. Rueda Cordero et al\(^22\) have established a hydro-mechanical model for hydraulic fracture propagation and its interactions with frictional natural fractures. Feng et al\(^23\) developed a fixed-point hydraulic fracturing method for coal seam rockburst prevention, and they found that resistance increasing and energy releasing are the two main roles of hydraulic fracturing in order to prevent rockburst. Chukwudozie et al\(^24\) have constructed a variational phase-field model for hydraulic fracturing in porous media. Cai and Liu\(^25\) proposed an upward cross-seam hydraulic fracturing method for permeability enhancement. They found five stages in the process of hydraulic fracturing, which was divided into stages of energy accumulation, initiation of microcracks, damage localization, localized fracture propagation and interaction, resistance losing of coal, and fracture expansion rapidly. By using deep hole blasting for permeability increasing, Sampath et al\(^26\) have conducted a theoretical overview of hydraulic fracturing breakdown pressure. Li et al\(^27\) studied the mechanism of breaking coal and rock using pulsating pressure wave in a single low permeability coal seam. To optimize drilling arrangement of rock cross-cut and based on the theoretical analysis of influenced radius, Roche et al\(^28\) have conducted a study of 3D modeling of hydraulic fracturing and stress perturbations during fluid injection. Patel et al\(^29\) have estimated hydraulic fracture permeability using stimulation pressure data. In addition, Yang et al\(^30\) studied the mechanism of a “strong-soft-strong” structure for rock cross-cut uncovering coal seam. They concluded that the thickness of the soft and strong layers in this structure should be 4 and 2 m, respectively, to attain a better prevention of coal and gas outburst. Rayudu et al\(^31\) simulated three-dimensional hydraulic fracture propagation using displacement correlation method. Although many researches of hydraulic fracturing have been conducted in coal mines for the purpose of permeability enhancement of coal seam and prevention of coal and gas outburst, it is still not very well understanding of the effect of permeability enhancement on low permeability coal seam, especially for the case of rock cross-cut uncovering coal in deep mining. As mining depth increasing, high in situ stress is unavoidable in deep mining. In this fashion, stress-sensitive effect would cause many problems in hydraulic fracturing such as high initial pressure and fracture closure.\(^32\),\(^33\) In-depth research is hence needed to deal with the high in situ stress and to further increase the permeability enhancement effect in hydraulic fracturing (HF) process in deep coal mining.

For the purpose of improving the effect of permeability enhancement in HF under rock cross-cut coal uncovering condition, this study introduces a permeability enhancement technique of HF sand-carrying for rock cross-cut that based on the “water-sand” type in HF. In this study, a brief introduction of engineering geology background is provided in Section 2. Numerical modeling of permeability enhancement in HF using RFPA is conducted, and modeling results are presented in Section 3. Subsequently, mechanism analysis of HF sand-carrying for permeability enhancement is discussed.
in Section 3. Finally, a field test of HF sand-carrying and effect of permeability enhancement in HF test are presented and discussed in Section 4.

2 | BRIEF INTRODUCTION OF ENGINEERING GEOLOGY

Panji mining area is located on the north of the Huaihe River, which belongs to the Huainan City, Anhui Province, P. R. China. The west-1 (13-1⑧) panel is located in southern part of the Panji mining area, which is about 9.3 km and 5.8 km along the strike (E-W) and dip direction (S-N) on the projection of contour line at −900 m ground level, respectively (Figure 1).

The tailgate of 13⑧ coal seam is located at the rise entry of roof in the west-1 (13-1⑧) panel. The location of field test for rock cross-cut coal uncovering is designed in the roof of the tailgate rise entry of west-1 (13-1⑧) panel. The rise entry of tailgate is excavated in a 24.5 m normal distance with a 16° inclined angle from the floor of 13-1⑧ coal seam. It is about 25 m normal distance for uncovering coal seam until to the roof of 13-1⑧ coal seam, which results in about 130 m for regional elimination of coal and gas outburst potential. According to the gas geological data, the initial gas pressure and gas content of the uncovering coal seam area are 6 MPa and 15 m³/t, respectively. Meanwhile, the water content of the interested coal seam area is about 2.04% with an original permeability coefficient of 0.0324 m²/MPa²/d. In addition, the mining elevation of uncovering coal seam is −750 m with an average thickness of 2.9 m and with 150-170°∠4-8° of coal seam occurrence.

Table 1 presents the general condition of roof and floor for 13-1⑧ coal seam. According to the geological survey, it is found that no obvious large fault is identified within 100 m spatial volume of the uncovering coal area and a relatively simple tectonic geological condition is found for the interested uncovering coal area. More information related to the spatial location of the 13-1⑧ coal seam, tailgate rise entry of west-1 (13-1⑧) panel, and other information are provided in Section 5.

3 | ANALYSIS OF HF PERMEABILITY ENHANCEMENT IN DEEP MINING

3.1 | Numerical model set-up

As stated in Section 2, geological conditions of the roof of tailgate rise entry of west-1 (13-1⑧) panel are taken as the engineering background to construct the numerical models, which is simulated by using Realistic Failure Process Analysis (RFPA) software of rock fracturing analysis tool. The calculation method is based on finite element theory and statistical damage theory. The method considers the heterogeneity of material properties and the randomness of defect distribution. The statistical distribution hypothesis of the material properties is combined with the numerical calculation method to deal with the failure of the element that meets the given strength criterion, so that the numerical simulation of the failure process of nonuniform material can be realized. Several key features are simulated and monitored during the HF modeling such as the evolution law of crack propagation, acoustic emission, and variation of permeability. Based on the geological conditions, the model dimension is 60 m long and 30 m high and the model is discretized into 180,000 elements.

For the purpose of understanding the difference in HF permeability enhancement between shallow and deep coal and rock masses, two scenarios are considered in the modeling: Case A and Case B with mining depth of 400 and 750 m, respectively. Based on the numerical models, different vertical stresses are applied on the top boundary to consider the shallow and deep cases, that is, 10 and 18.75 MPa of vertical stress are applied for Case A and Case B. The bottom of model is fixed, and the left and right boundaries are constrained in horizontal direction.

To make the numerical model comparable to the filed HF tests and to simplify the numerical models, as shown in Figure 2, five fracturing boreholes are arranged in the coal seam with a borehole diameter of 94 mm and with an interval of 10 m. The initial gas pressure of coal seam is assumed as 6 MPa and the initial hydraulic water pressure is set as 5 MPa with a 0.5 MPa/Step pressure increment. The pressure is increased gradually until the coal seam is fully damaged.

FIGURE 1 Location of Panji Coal Mine
Based on previous laboratory test results of coal and rock specimens, the modeling parameters of each rock layer are presented in Table 2.

### 3.2 Discussion of HF permeability enhancement

It is known that coal masses are a porous medium that is rich in pores and fissure. When the coal masses are under hydraulic fracturing, a tensile force is formed along the side of pores and microcracks due to the action of water pressure. This tensile force increases continually during the hydraulic fracturing progressing. Once the generated tensile force reaches the initiation pressure of coal masses, tensile fracture is then initiated and propagated and interacted with the preexisting fractures. Under the driving force of increased high water pressure, new fracture is created and propagated and would form a new chain-like effect of newly generated fractures. In this manner, a complex and interconnected fracture network system is eventually formed within the coal masses, which can increase the permeability of...
coal seam and thus can provide a good flow path for the gas flow. Meanwhile, in the process of HF, coal mass is undergoing progressive damage associated with the occurrence of acoustic emission due to the generated complex fracture network system.

Structure and mechanical properties of coal mass are changed, and the integrity of coal mass is damaged.

Crack propagation and evolution patterns of coal seam during the HF process are shown in Figure 3. In addition,
the relation between the number of acoustic emission, energy of acoustic emission, and the modeling steps are present in Figures 4 and 5.

It is seen from Figure 3 that coal and rock mass around fracturing borehole is subjected a process of crack initiation of preexisting pores and microcracks, to propagation of induced cracks and newly created cracks, and to a complex fracture network system under the action of water pressure during the HF modeling. Meanwhile, from Figures 4 to 5, it is observed that occurrence of the acoustic emission is obvious, which is associated with gradually damage of coal masses. In addition, under the same modeling steps, from Figures 3 to 5, it is found that the crack propagation and development show more intensity trends for Case A (shallow depth) when compared with Case B (deep depth). Further, when comparing the number and energy of acoustic emission between Case A and Case B, it is found that shallow depth case has higher number and larger energy of acoustic emission. This observation may be caused by the different vertical stresses between the two cases. Low and high in situ stress is expected for Case A and Case B. For low in situ stress state, relatively low crack initiation pressure is needed to create new cracks or extend preexisting cracks. However, relatively high crack initiation pressure is required and more difficult to propagate and develop the cracks during HF for the case of high in situ stress state.

Based on the formation and propagation of cracks and the number and energy of acoustic emission in the HF modeling, three distinct stages are summarized as:

### 3.2.1 Stage 1: Energy increases slowly and crack initiation

In this stage, seepage is the main way for high-pressure water that penetrate into the preexisting pores and microcracks. This seepage process causes a driving effect to the gas inside

the pores and microcracks, which can be expressed as water flooding gas phenomenon. This phenomenon causes the gas pressure to increase gradually. As the HF progresses, many isolated microcracks are created and developed gradually around fracturing borehole. Further, more intensive of cracks are formed along the horizontal direction of hydraulic borehole when compared with that along the vertical direction. At this stage, no obvious coal damage is observed and small number and energy of AE events are also identified.

### 3.2.2 Stage 2: Damage localization and progressive failure of coal masses

As the applied water pressure increases, extent of crack development is continuously growing around the fracturing borehole due to high tensile force that formed by high-pressure water. The main fractures are propagated and extended continuously in the horizontal direction at both sides of the fracturing borehole. Meanwhile, some sporadic microcracks are formed at the tip of the main fracture. In this manner, damage localization of coal mass is generated due to the propagation of main fractures and a progressive damage process is expected as the water pressure increases in the HF. At this stage, main fractures are developed relatively faster and obvious increasing trends are also found for both the number and energy of AE events. For instance, a rapidly increasing of slops are observed for both the accumulate number and energy of AE events in Figures 4 and 5.

### 3.2.3 Stage 3: Crack instability development and fracture propagation

As progressing of the FH, energy accumulated from the high-pressure water increases gradually, which would cause high tensile force at the sides of cracks. Once the tensile force reaches the critical pressure of the fracture instability
and propagation, a rapid jump of AE number is observed and fracture and cracks around the main fractures accelerate development and propagation, which causes rapidly extension and development of the main fracture near the hydraulic borehole. Meanwhile, a number of irregular cracks are formed at the tips of the main fracture and some cracks are interconnected between the adjacent fracturing boreholes. Because of the multi-interaction of cracks and the main fractures within the coal masses, a 3D fracture network system with high conductivity is formed within the coal masses and hence increases the gas permeability of the coal body in this stage.

It is well known that gas permeability of coal mass can be characterized by a factor of permeability coefficient; in general, the higher the gas permeability, the greater the permeability coefficient. To further check the effect of shallow and depth mining on hydraulic fracturing, Figure 6 shows the variation curves of the permeability coefficient. It is seen that the permeability of coal mass increases obviously due to the effect of hydraulic fracturing. A low permeability coefficient is observed before the HF (red dash line in Figure 6) and the permeability coefficient increases gradually as HF progressing due to the development and propagation of cracks around the fracturing borehole and the propagation of the main fracture (blue and cyan dash lines in Figure 6 at modeling steps 30 and 40). In addition, relatively high permeability coefficient if identified between the adjacent fracturing boreholes indicates that cracks are interconnected and well developed among the adjacent fracturing boreholes. A relatively higher flow rate is expected within this fracture network system.

When the permeability coefficient between Case A (shallow depth) and Case B (deep depth) is compared, from Figure 6, it is found that the maximum permeability coefficient is 65 m/d for the Case A, which is about 3.1 times higher than that of Case B (21 m/d). This observation is not surprising as discussed previously. Because of low in situ stress state for Case A, the cracks are easier to develop and propagate when compared that with Case B with a lower gas permeability. In this manner, low gas permeability is expected for coal mass in deep mining when compared that with shallow mining.

3.3 Mechanism analysis of HF

The coal mass is rich in preexisting pores and microcracks, and the high-pressure water is acted as water wedges and would enter into weak planes within the coal mass such as the pores, joints, and cracks in the HF process. Under the action of high-pressure water, tensile force is generated at both sides of the weak planes. When the tensile force reaches the critical value of stress instability at the tips of weak plane, tensile failure is occurred and expanded and propagated continuously. Meanwhile, many small secondary new cracks are also generated due to continuous action of high-pressure water. Many small cracks are then interacted with the main fracture and would be interconnected to the main fracture and thus form a complex fracture network system. Due to cutting effect of the complex fracture network system within the coal mass, a chain effect is formed to destroy the structure and integrity of coal seam, which associated with the high-pressure water-driving weak planes to develop, to propagate, to create secondary cracks, to interaction, to multiconnect, and to form a complex fracture network system. In this way, connectivity of the preexisting pores and microcracks is increased largely, and thus, the permeability of coal seam is increased due to the HF.

At the end of hydraulic fracturing, a force component that is perpendicular to the crack surface is formed in coal mass due to effect of in situ stress (vertical and horizontal stress components) on the hydraulic fracturing. Due to the effect of this force component, this crack is normally in compression state. For the HF in shallow mining depth with relative low in situ stress state, lower force component that is perpendicular to the crack surface is expected and it is not easy to close the
cracks and the cracks thus can maintain a certain degree of aperture, as shown in Figure 7A. Because the influence of in situ stress on the effect of HF, a better effect of HF permeability enhancement is expected. In addition, when the HF is applied to the coal seams in deep mining depth, a larger force component that is perpendicular to the crack surface is created compared with that in shallow mining depth case. After the HF, the cracks are easy to close under such a large force, which result in a very small or even zero aperture for these cracks.

As shown in Figure 7B, the crack morphology shows a close trend of the crack apertures, which leads to a rapidly decreasing of the permeability of coal seam and results to a very poor effect in the HF permeability enhancement. To keep a certain aperture of HF cracks in coal masses during HF process under deep mining case and to strengthen the HF permeability enhancement, based on typical HF technique, a certain amount of sand is added in the action water to play as proppant role in the HF. As mentioned, microcracks would initiate, propagate, and interconnect at the weak planes within coal seam under the driving of high-pressure water. Due to the sand in the high-pressure water, the sand would enter into HF cracks in this type of HF sand-carrying. The sand can help to main a certain aperture of cracks and thus to produce a support effect to the cracks. A pair of force and reaction force relation is formed between this kind of support force, the force component that is perpendicular to the crack surface and the tensile strength of coal mass. Because of high tensile strength of sand that settled within the cracks, the crack closure is then hindered effectively (as shown in Figure 7C). The crack would keep a certain aperture after HF for the deep mining scenario.

As discussed, high-risk potential of coal and gas outburst is closely related to the rock cross-cut coal uncovering, especially for deep mining with relatively low permeability of coal seam due to high in situ stress. To reduce the risk of dynamic disasters such as coal and gas outburst, HF technique can be used to increase the permeability of coal seam. Predrainage of gas in the rock cross-cut coal uncovering area is recommended so that the gas pressure and content could meet the requirement of “prevention regulation of coal and gas outburst” (i.e., gas pressure should be less than 0.74 MPa, and gas content should be less than 8 m³/t). However, in the scenario of deep mining, as mentioned above, the HF cracks are easy to close after HF due to the effect of high in situ stress, which would reduce the permeability rapidly and lead to a poor HF permeability enhancement.

For the purpose of improving the HF permeability enhancement of rock cross-cut coal uncovering, this study proposed a strengthened permeability enhancement approach, which uses a “water-sand” type for the HF. In this approach, a typical HF technique is applied firstly for the coal uncovering area and a HF sand-carrying is then conducted in latter stage. In other words, two stages are considered herein. (a) Typical HF: A preliminary HF area and fracture network system are created in the coal mass using typical HF method. The permeability is increased initially; (b) HF sand-carrying: sand-carrying HF is then followed by the first stage. On the one hand, the initial HF area is subjected secondary HF effect, which can lead to fully developed and propagated of cracks. On the other hand, the sand is wedged into the crack tips due to the high-pressure water and the cracks are kept in an open state with certain apertures. Under the action of continuous high-pressure water, the cracks are further expanded and propagated. Due to support effect of sand (suspended in the high-pressure water) to the cracks, the crack closure is hindered and the aperture of cracks can maintain to a certain level instead of closing after closing of HF process. In this way, a high conductive of fracture network system is thus formed, which can assist the gas flow and thus increases the permeability largely. Furthermore, because the sand restrains the closure of HF cracks, the coal mass still has a relatively high permeability during the latter period of gas drainage in deep mining.
4 | FIELD TEST OF HF FOR COAL UNCOVERING IN CROSS-CUT

Based on the above analysis of permeability enhancement between the shallow and deep mining depth in Section 3 and mechanism analysis of HF sand-carrying and for the purpose of coal and gas outburst issue triggered by rock cross-cut coal uncovering, filed application of permeability enhancement using HF sand-carrying was conducted at the roof of tailgate rise entry of west-1 (13-1") panel. Details are provided in the following.

4.1 | Test plan of field application

According to the geological conditions of the coal uncovering area in the rock cross-cut at the roof of tailgate rise entry of west-1 (13-1") panel, totally, five HF boreholes were designed and arranged in the field tests. The HF boreholes were numbered from borehole 1# to borehole 5# and with 50-m interval between two HF boreholes. To examine the effectiveness of hydraulic fracturing parameters during HF process, three auxiliary boreholes were arranged in the HF area and these boreholes were named as auxiliary 1#, 2#, and 3# with a 20-m spacing between two auxiliary boreholes. The diameter for all the boreholes was 94 mm.

Arrangement of drilled HF boreholes and spatial locations of the boreholes, relation among the coal seam, boreholes, tailgates, and coal uncovering area are shown in Figure 8. As shown in Figure 8, the HF boreholes of 1#, 2#, and 3# (blue lines) and auxiliary boreholes of 1#, 2#, and 3# (red lines) are drilled in the floor entry of 1252(3). Furthermore, 4# and 5# boreholes of HF are drilled at the starting point of the roof of tailgate rise entry.

In addition, design parameters of boreholes are shown in Table 3. To prevent the water leakage at the tunnel surface from the surrounding rock mass during the HF process, full section of spray grouting reinforcement was performed within 30 m around the HF boreholes prior to HF practice.

4.2 | Field implementation of permeability enhancement using HF

As mentioned above, it is reaffirmed that “water-sand” type of fracturing fluid was used in the HF tests in order to improve the permeability enhancement of uncovering coal area in deep mining. For each fracturing borehole, a typical HF
was conducted as the first stage and sand-carrying water was then carried out as the second fracturing stage. For sand selection, it should be mentioned that the sand should have certain compression strength and antiwear capacity with a relatively low density. The size of sand grain should be in a uniform distribution. In addition, the sphericity and roundness of sand particle should be close to 1. In the field tests, the HF was performed in the order of 1#, 2#, 3#, 4#, and 5# boreholes. To monitor pressure of injection water, a pressure sensor was installed at the collar of fracturing borehole in the HF process. Meanwhile, gas content was also monitored for area of borehole collar and in the entry through the digital images of fracturing pump and borehole neck by using camera. Observations of each fracturing borehole are summarized as follows:

1# borehole: Totally about 226 m$^3$ of water was injected into the 1# borehole with a 9.4 hours of fracturing time. Roughly 120 and 106 m$^3$ of water were injected into the borehole at the 1st and 2nd stages, respectively. The initiation cracking pressure was 29.1 MPa. Within the area of 30 m around the 1# borehole, a wet area with about 1 m diameter was found in the tunnel roof and no water leakage phenomena were observed around the tunnel and other closed tunnels after 20 days of HF. In addition, high-pressure water was gushed out in the three auxiliary boreholes after 8 m$^3$ water was injected into the 1# borehole. Figure 9 shows photographs of field tests for the equipment (Figure 9A) and the three auxiliary boreholes (Figure 9B). Large amount of pulverized coal was also observed associated with the high-pressure water. The size of coal particle was between 3 and 5 mm in the initial stage and then changed to about 1 mm of coal particle size in the latter stages. Furthermore, the maximum gas concentration was about 10% at the collar of borehole and with a 3% mean value of gas concentration for the remaining monitoring process. No abnormal variation of gas concentration was observed in the drift.

2# borehole: Totally about 330 m$^3$ of water was injected into the 2# borehole with a 13.7 hours of fracturing time. About 170 and 160 m$^3$ of water were injected into the borehole at the 1st and 2nd stages, respectively. The initiation cracking pressure was 25.8 MPa. When the injection water was reached to 250 m$^3$, water leaking was observed at the bottom of rock bolts in the drift roof area; however, it is observed that the quantity of leaked water is not large.

3# borehole: Totally 330 m$^3$ of water was injected into the 3# borehole with a 13.5 hours of fracturing time. About 170 and 160 m$^3$ of water were injected into the borehole at the 1st and 2nd stages, respectively. The initiation cracking pressure was 25.8 MPa. When the injection water was reached to 250 m$^3$, water leaking was observed at the bottom of rock bolts in the drift roof area; however, it is observed that the quantity of leaked water is not large.

### Table 3

| Borehole number | Azimuth (°) | Elevation (°) | Location | Depth (m) |
|-----------------|-------------|---------------|----------|-----------|
| HF. 1#          | 90          | 83            | Floor entry of 1252(3) | 52.2 |
| HF. 1#          | 270         | 46            | Floor entry of 1252(3) | 62.4 |
| HF. 1#          | 90          | 47            | Floor entry of 1252(3) | 80.9 |
| HF. 1#          | 0           | 61            | Start point of tailgate rise entry | 36.0 |
| HF. 1#          | 90          | 30            | Start point of tailgate rise entry | 77.2 |
| AU.1#           | -37         | 70            | Floor entry of 1252(3) | 54.2 |
| AU.2#           | -90         | 77            | Floor entry of 1252(3) | 51.8 |
| AU.3#           | -142        | 71            | Floor entry of 1252(3) | 54.2 |

Abbreviations: AU, auxiliary borehole; HF, hydraulic fracturing borehole.
this site area. The rest of the watering locations are basically maintained as a dripping in the drift walls.

4# borehole: Totally 330 m³ of water was injected with a 13.1 hours of fracturing time. Roughly 175 and 155 m³ of water were injected into the borehole at the 1st and 2nd stages, respectively. The initiation cracking pressure was 23.2 MPa. When the initiation cracking pressure of 4# is compared with that from 1# to 3# boreholes, a decreasing trend of initiation crack pressure is found for 4# borehole. This may be caused by the decreasing of coal strength due to the water rate increasing of coal seam after the HF process of the previous three fracturing boreholes.

5# borehole: Totally 260 m³ of water volume was injected with a 10.5 hours of fracturing time. Roughly 140 and 120 m³ of water were injected into the borehole at the 1st and 2nd stages, respectively. The initiation cracking pressure was 21.2 MPa. As shown in Figure 11, grout spalling and dropping phenomenon was observed on the left side wall of drift in the front of start point at the roof of tailgate rise entry during the HF progressing. In addition, multiple watering locations were also identified within 4 m distance from the heading work face.

Due to the fact that certain amount of sand is added in the high-pressure water at the 2nd stage of HF permeability enhancement field tests, a support effect from sand particles can be generated for the cracks that created by the HF-associated cracks that connect to the HF cracks. In this manner, a certain aperture of cracks would be kept without closure due to the high in situ stress after HF when the water pressure is gone. In other words, a high conductivity capacity for gas flow is formed due to the complex fracture network system within the coal mass. Coal permeability enhancement can be therefore obtained by using this two-stage “water-sand” HF approach.

To investigate the effect of HF sand-carrying in the permeability enhancement, as shown in Figure 12, a certain number of examination boreholes were drilled into the HF area after the HF tests as stated in Section 5. The layout of borehole was aimed to cover the coal seam area with about 120 and 320 m in the radial and axial direction of the tested tunnel. Coal samples were collected from the boreholes, and key features of coal specimens were tested such as water content and gas concentration. Meanwhile, comparison of gas drainage volume and concentration of coal seam located in various locations was made between the typical HF and the HF sand-carrying–treated coal seam areas. The comparison coal seams area was selected based on locations of unfracturing area of 13-1 coal seam, 13-1 coal seam, and other uncovering coal seam areas.

Considering facts that small amount of the gas extraction for a single drainage borehole and the influence of sealing quality and other factors for certain boreholes, large variations of gas extraction among single borehole are expected in the field tests. It is hence necessary to find an alternate way to evaluate the extraction effect. To make the evaluation in a practical manner, 100 gas extraction boreholes were considered as an extraction evaluation unit herein. The gas extraction boreholes were arranged in a pattern of 5 m × 5 m (the details of extraction boreholes were not intended to present here due to the paper length limitation). Gas extraction boreholes in an evaluation unit were merged into one group, which was connected to the gas drainage system. In addition, a monitoring meter gauge was installed to measure the amount of gas extraction for the unit of 100 boreholes. To
ensure the gas drainage quality, a technique of “two plugs and one injection” with pressured grouting sealing was used for all the examination boreholes of gas extraction.

4.3 | Distribution of water content for coal seam

Water content is one of the most important factors used to evaluate the HF permeability enhancement. To obtain an overall distribution characteristics of water content within the fracturing area of the HF sand-carrying tests, based on the test data of water content within the coal seam, the distribution of water content is characterized using interpolation method in MATLAB and the distribution of water content is shown in Figure 13 (horizontal plane projection).

It can be seen from Figure 13 that the water content in the HF-treated area shows approximately symmetrically distribution along the tunnel axial and radial direction of the roof at the tailgate rise entry of west-1 panel. Relatively higher water content is observed in the coal seam around the fracturing boreholes when compared with that of surrounding coal seam. The maximum water content is 7.9%, which is 3.9 times higher than that of raw coal seam. In addition, it is also found that the water content of coal seam basically reached above 4.1% in the range of 45 m around the fracturing boreholes, which is roughly 2 times of water content of raw coal seam. In this manner, it is concluded that the influence area of HF sand-carrying can reach up to 45 m around the fracturing boreholes based on the water content distribution.

4.4 | Characteristics of gas permeability

It is well known that gas permeability is a key factor to evaluate the potential efficiency of gas drainage within coal seam. To investigate the effect of permeability enhancement on the coal seam area using HF sand-carrying method, a direct measurement method widely used in the coal mine was performed to determine the permeability coefficient of coal seam.

According to the theory of coalbed radial unstable flow in coal seam and based on the parameters of coal seam gas pressure after HF and parameters of gas extraction boreholes, the permeability coefficient of coal seam is calculated and it is estimated in the range of between 0.6978 m²/MPa²/d and 0.9869 m²/MPa²/d for the coal seam area after the HF sand-carrying field application. The permeability coefficient of coal seam is increased from 21.5 to 30.5 times when compared with that of the raw coal seam (0.0324 m²/MPa²/d). It is concluded that the permeability of coal seam increases notably using HF sand-carrying method and a better permeability enhancement is achieved for the coal seam.

4.5 | Gas drainage effect

In the HF sand-carrying approach, as mentioned, the cracks that formed by HF can be kept to a certain aperture within the coal seam due to the support effect of sand. In the meantime, coal gas that initially adsorbed in the coal seam is easier to desorb under the action of drainage-negative pressure, which is beneficial to the gas drainage.

Gas drainage was carried out after the construction of gas extraction boreholes in the HF-treated coal seam area. When the gas drainage was lasted 50 days, gas drainage effect was assessed by the content and concentration of gas from the 100
boreholes in the evaluation unit. Figure 14 shows the comparison of gas content and concentration at three coal seam locations. The content and concentration of gas drainage are compared among the coal seam in three areas: 13-1 coal seam area without HF (square with black line), 13-1 coal seam area with typical HF (circle with red line), and coal seam area with HF sand-carrying (triangle with blue line).

It is seen from Figure 14 that both gas content and concentration of typical HF and HF sand-carrying are higher than those of unfracturing in the investigation coal seam area within an evaluation unit. Three stages can be divided based on the curve trends, that is, stable increasing, peaking, and stable stages. When comparing with the gas content and concentration in the evaluation unit from unfracturing and typical HF area, a notable peak stage is observed for the coal area from HF sand-carrying. Furthermore, for the HF sand-carrying, it is seen that the maximum extraction quantity is 1.2 m$^3$/min with an average extraction quantity of 1.2 m$^3$/min within the evaluation unit of 100 extraction boreholes. The maximum gas concentration is 75.3% with an average gas concentration of 55.6%. Similarly, it is found that the maximum extraction quantity and gas concentration are 0.7/0.48 m$^3$/min and 49.7/29.9% for the typical HF area. Besides, the average gas extraction quantity and concentration are 0.33 m$^3$/min and 16.4% for the unfracturing areas. When compared to the gas extraction quantity in the area under HF sand-carrying, the maximum value is about 1.7 times higher than that of typical HF area and the average value is about 1.7 and 2.5 times higher than that of typical HF and unfracturing areas. When comes to the gas concentration in the investigation area under HF sand-carrying, the maximum value is about 1.5 times higher than that of typical HF area and the average value is about 1.9 and 3.4 times higher than that of typical HF and unfracturing areas.

In addition, the HF sand-carrying field application shows that the time period of increasing stage for gas content and concentration is normally about 2-8 days, the time period for peaking and stable stages are about 9-12 days and up to 30 days, respectively. The gas extraction had a remarkable drainage time and high efficiency.

4.6 | Gas distribution characteristic in coal seam

To deepen the understanding of the gas distribution in the coal seam area under the HF sand-carrying treatment, gas pressure and content were measured within coal seam with a 15-m distance along the center radial line of the rock cross-cut, as shown in Figure 15. It is seen from Figure 15 that an approximately “U” shape distribution is found for both gas pressure and gas content, which is distributed with a15-m distance from the central part of rock cross-cut. As distance from the centerline increases, both gas pressure (Figure 15A) and gas content (Figure 15B) increase. Meanwhile, both gas pressure and content are relatively low around the central part of rock cross-cut (i.e., 0-5 m distance) due to the effect of HF sand-carrying. The maximum gas pressure and content are 0.29 MPa and 4 m$^3$/t, respectively. Both gas pressure and content are smaller than the requirement of critical values of “prevention regulation of coal and gas outburst” (gas pressure should be less than 0.74 MPa, and gas content should be less than 8 m$^3$/t according to the Coal Mine Safety Regulations). In this way, it is hence concluded that a better prevention effect of coal and gas outburst is achieved using the HF sand-carrying approach for target coal seam area.

5 | CONCLUSIONS

Coal and gas outburst disasters are prone to occur in rock cross-cut coal uncovering in deep underground coal mines.
To reduce the risk of coal and gas burst under rock cross-cut coal uncovering, a technique of permeability enhancement using hydraulic fracturing with sand-carrying is proposed in this study. Numerical simulation was conducted to understand effect of shallow and deep depth on the permeability and the behavior of induced cracks using RFPA. The mechanism of HF was discussed to further illustrate the potential application of this method under high in situ stress in deep mining.

In the process of HF, high-pressure water is entered into the pores and microcracks in the form of water wedge, which drives the development and propagation of the cracks continuously. The evolution of cracks can be divided into three stages: the energy slowly increasing and crack initiation, damage localization of coal seam and gradually failure, and crack instability expansion and formation of a complex fracture network system.

In the process of the permeability enhancement using HF sand-carrying, “water-sand”-type injection high-pressure fluid carries the sand into the HF cracks, which creates a support force on the crack surface, and prevents the closure of cracks. A fully developed fracture network system with high flow conductivity capacity is created, and thus largely increases the gas permeability.

Three stages of gas extraction content and concentration are identified as stable increasing, peaking, and stable stages. A notable peak stage is observed for the treated coal area under HF sand-carrying. A time period for stable gas extraction stage can be up to 30 days, which has a remarkable drainage time in gas drainage practice. Furthermore, for the treated coal seam target area of HF sand-carrying, the average extraction quantity and gas concentration are much higher than those from the areas of typical HF and unfracturing areas.

After the implementation of HF, the permeability coefficient is much higher than that from the raw coal seam. In addition, a “U” shape distribution is found for both gas pressure and gas content. Both gas pressure and content are smaller than the requirement of critical values. A good prevention effect of coal and gas outburst can be achieved.

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ORCID
Cheng Zhiheng https://orcid.org/0000-0002-1825-6173
Zou Quanle https://orcid.org/0000-0002-6395-0455

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