A new cross-borehole hydraulic caving technique in the coal seam with a soft layer for preventing coal and gas outbursts during coal roadway excavation

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Funding information
Changjiang Scholars and Innovative Research Team in University, Grant/Award Number: IRT16R22; Henan Province Industry-University-Research Cooperation Project, Grant/Award Number: 162107000040; China Postdoctoral Science Foundation, Grant/Award Number: 2017M622343

Abstract
Predrainage of gas by cross-boreholes is an important method to prevent coal and gas outbursts in the process of a coal roadway excavation. Limitations of technologies and poor effects of preventing coal and gas outbursts occur in the coal seam with a soft layer. In this study, a new hydraulic caving technology for cross-boreholes has been proposed to solve this problem. A CT equipment was used to observe the development of coal fissures around cross-boreholes in the coal seam with a soft layer. The plastic zone range and permeability distribution of ordinary hydraulic slotting technologies and the new hydraulic caving technology also were compared by numerical simulation. The field test of hydraulic caving was taken in the Xuehu Mine (China). The results show that the fracture development degree of soft coal is greater than that of hard coal at the same distance from cross-boreholes. The fracture development degree in the plastic zone is greater than that in the elastic zone. The hydraulic caving technique can achieve the same effect as the ordinary hydraulic slotting with less workload. The mass of coal discharged from a cross-borehole was 1.15 t/m and the average methane concentration of single drainage borehole increased by 1.09-4.1 times, and the average methane extraction amount of single drainage borehole increased by 6.06 times. Elimination of coal and gas outburst had been completed after 110 days of extraction in the area of hydraulic caving, and Q and S values are lower than the critical value during roadway excavation. It is conclusion that hydraulic caving technique can effectively improve the permeability and rapidly eliminate coal and gas outburst in the coal seam with a soft layer.

KEYWORDS
coal and gas outbursts, coal roadway excavation, cross-boreholes, gas extraction, hydraulic caving
Coal mine methane (CMM) is a kind of coal-associated energy that can be used directly.\(^1\) The gas storage has reached 36.81 trillion cubic meters with the depth of <2000 m in China.\(^2\) In normal conditions, gas extraction is required before mining methane-bearing coal seams to eliminate coal and gas outburst and use methane reasonably.\(^3\)–\(^6\) As shown in Figure 1, gas predrainage is one of the effective methods to prevent coal and gas outbursts during coal roadway excavation. Cross-boreholes and in-seam boreholes are usually two types of boreholes layout for gas predrainage.\(^7\)–\(^9\)

With the increase of mining depth, the difficulty of gas extraction increases in the “three-high and one low” coal seam whose characteristics are high ground stress, high gas content, high gas pressure, and low gas permeability.\(^10,11\) Therefore, how to enhance the permeability of coal seam and improve the efficiency of gas drainage, especially complex geological conditions (e.g., coal seam with a soft layer), is a difficult problem for experts and scholars all over the world.\(^12\)

At present, methods of coal seam permeability enhancement include \(N_2\) injection, deep hole presplitting blasting,\(^13\) hydraulic fracturing,\(^14\) hydraulic flushing,\(^15,16\) hydraulic slotting, and other methods.\(^17\)–\(^22\) The permeability has shown a trend of increasing sharply, slightly decrease, and then stable at a constant value after injecting \(N_2\) in \(CO_2\)-rich low permeable seam.\(^23\) Deep hole presplitting blasting measures have limited application due to its complex technology and high risks.\(^24\) Hydraulic fracturing cannot control the direction and boundary of fracturing in the complexity of coal seam. Although a great number of researches on directional fracturing technology have been studied by many experts and scholars,\(^25\)–\(^27\) hydraulic fracturing is easy to cause stress concentration in coal body, which leads to coal and gas outburst.\(^28\) Hydraulic flushing can enlarge borehole diameter by flushing coal body with high-pressure water jet, which is equivalent to large diameter borehole, and the larger the borehole diameter is, the larger the pressure relief range of the borehole and the permeability of the coal around the borehole are.\(^29\) Hydraulic slotting can enhance permeability by cutting coal seam fractures with high-pressure water jet. Therefore, hydraulic flushing and hydraulic slotting are often used to enhance permeability in coal mines.

A lot of research on hydraulic slotting have been done in theoretical researches. Liu et al\(^30\) established a theoretical constitutive model for damage of coal seam with hydraulic slotting. Si et al\(^31\) and Li et al\(^32\) have studied the variation of stress distribution around the borehole of hydraulic slotting borehole and determined the basic parameters of the hydraulic slotting. Zhang et al\(^16\) have analyzed the strain-softening behavior of coal around hydraulic slotting borehole and the influence of coal failure on permeability. Zou et al\(^33,34\) have studied the change of pore-structure characterization and the law of gas adsorption characterization of coal after boreholes after hydraulic slotting by Laboratory and industrial tests. Zhao et al\(^35\) have studied the distribution law of gas flow field around hydraulic slotting borehole in anisotropic coal. In technology, Zhang et al\(^16\) have studied the functional relationship between the groove depth of water jet and time, and the effect of different slotting depth on gas drainage efficiency. Zou et al\(^37\) have studied the stress distribution law of coal mass around different slotting angles of hydraulic slotting and pointed out the large slot inclination angle in soft coal seam and the small slot inclination angle in hard coal seam are beneficial to pressure relief. Shen et al\(^38\) have analyzed the factors causing drill-spray during hydraulic slotting and put forward the method to prevent drill-spray from hydraulic slotting. Zou et al\(^39\) have revealed the fluid-solid coupling property of gassy coal to hydraulic slotting by established experimental system.

The coal seam occurrence conditions are complex in China, and the soft-hard coal seams and meteorite-mixed coal seams are widely distributed. The above research and application of hydraulic technologies are only for single strength coal seams, so these have great limitations in application. This paper is based on the evolution law of coal permeability around extraction boreholes. The elastic-plastic zone and permeability distribution of coal around cross-borehole in coal seam with a soft layer at the bottom were simulated. Then, a new hydraulic

FIGURE 1 Method of eliminating coal and gas outburst in single gas-bearing coal seam. A, Cross-boreholes extraction; B, In-seam boreholes extraction.
caving technology in coal seam with soft bedding was put forward, and the technical principle and construction details were introduced. Finally, engineering tests have been carried out in a coal mine, and good results have been achieved. It provides a new method for enhancing permeability of coal seams in complex occurrence conditions and has important guiding significance for improving gas extraction efficiency.

2 | NUMERICAL SIMULATION AND LABORATORY OBSERVATION

2.1 | The control equation

The study of the damage degree and permeability enhancement effect of coal around cross-boreholes by hydraulic caving in coal seam with soft bedding can provide basis and guidance for field test.

Assuming that the coal structure is isotropic, the gas-solid coupling stress-strain equation is as follows:

\[
\sigma_{ij} = \lambda \delta_{ij} + 2G \varepsilon_{ij} - \alpha \delta_{ij} \rho
\]

(1)

where \( \sigma_{ij} \) is the stress component; \( \lambda = \frac{E_v}{(1-2\nu)(1+\nu)} \) and \( G = \frac{E}{2(1+\nu)} \) are lame constants; \( \delta_{ij} \) is Kronecker symbol; \( \varepsilon_{ij} \) is strain component; \( \alpha \) is biot’s coefficient; and \( \rho \) is the gas pressure in coal seam.

The constitutive equation of gas-solid coupling based on the generalized Hooke’s law is as follows:

\[
G u_{i,j} + \frac{G}{1-2\nu} u_{j,ii} + \alpha p_i + F_i = 0
\]

(2)

where \( u_i \) and \( F_i \) is the component of the body force and displacement in the \( i \)th direction; \( \nu \) is the Poisson’s ratio.

The volumetric strain governing equation of coal mass can be expressed as:

\[
\varepsilon_{ii} = \frac{1}{2} (u_{ii} + u_{ji})
\]

(3)

In this study, the Mohr-coulomb criterion was used to judge the plastic failure of the coal body. The governing equation is as follows:

\[
F = \frac{1}{3} I_1 \sin \phi + \left( \cos \theta_p - \frac{1}{\sqrt{3}} \sin \theta_p \sin \phi \right) \sqrt{J_2 - c \cos \phi}
\]

(4)

where \( I_1 \) is the first principal stress tensor; \( \phi \) is the internal friction angle; \( J_2 \) is the second bias stress invariant; \( c \) represents the cohesion force; \( \theta_p \) is the stress Lode angle; and \( I_1, J_2, \theta_p \) can be calculated by the following formula:

\[
I_1 = \sigma_1 + \sigma_2 + \sigma_3
\]

(5)

\[
J_2 = \frac{1}{3} (\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - \sigma_1 \sigma_2 - \sigma_2 \sigma_3 - \sigma_3 \sigma_1)
\]

(6)

\[
\theta_p = \arctan \frac{2 \sigma_2 - \sigma_1 - \sigma_3}{\sqrt{3} (\sigma_1 - \sigma_3)} - \frac{\pi}{6} \leq \theta_p \leq \frac{\pi}{6}
\]

(7)

where \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the first, second, and third principal stresses.

Coal is an elastoplastic material with strain-softening characteristics. After soft stratified hydraulic acupoints, the stress areas around the cave can be divided into elastic zone, plastic softening zone, and plastic failure zone.

The plastic softening zone and the plastic failure zone can refer to as the plastic zone collectively. After the stress areas around the cave can be divided into elastic zone, plastic softening zone, and plastic failure zone.

The plastic softening zone and the plastic failure zone can be referred to as the plastic zone collectively. After the coal body enters the plasticity, the cohesive force was decreased, so the governing equation of the cohesive force change in the plastic softening zone and the plastic failure zone is as follows:

\[
c = \begin{cases} 
 c_0, & \gamma^p = 0 \\
 c_0 - \frac{(c_0-c_w)\gamma^p}{\gamma^{p*}}, & 0 < \gamma^p < \gamma^{p*} \\
 c_w, & \gamma^p \geq \gamma^{p*}
\end{cases}
\]

(8)

where \( c_0 \) is the initial cohesion force, \( c_w \) is the residual cohesion force, \( \gamma^p \) is the equivalent plastic shear strain, and \( \gamma^{p*} \) is the residual plastic equivalent shear strain. \( \gamma^p \) is calculated by the following formula:

\[
\gamma^p = \frac{1}{1+\nu} \sqrt{\frac{3}{2} (\varepsilon^p_1 - \varepsilon^p_3)^2 + (\varepsilon^p_2 - \varepsilon^p_3)^2 + (\varepsilon^p_3 - \varepsilon^p_1)^2}
\]

(9)

where \( \varepsilon^p_1, \varepsilon^p_2, \) and \( \varepsilon^p_3 \) are the first, second, and third main plastic strains, respectively.

After hydraulic caving, the permeability of the coal around the cave will change accordingly, the governing equation of permeability change can be expressed as follows:

\[
k = \begin{cases} 
 k_0 e^{-\omega}, & \gamma^p = 0 \\
 k_0 \left( 1 + \frac{\gamma^p}{\gamma^{p*}} \right) e^{-\omega}, & 0 < \gamma^p < \gamma^{p*} \\
 k_0 (1+\xi) e^{-\omega}, & \gamma^p \geq \gamma^{p*}
\end{cases}
\]

(10)

where \( k_0 \) is the initial permeability of the coal seam, \( \omega \) is the cleat volume compressibility, and \( \xi \) is the jump coefficient of permeability.
2.2 | **Numerical model**

In order to study the plastic failure range and permeability changes of the coal mass around the cave after the hydraulic caving, a two-dimensional numerical model with hard coal at the top and soft coal at the bottom had been established. The sizes of the roof, hard coal, and soft coal were 1 × 20 m, 2 × 20 m, and 1 × 20 m, and the cross-borehole diameter was 0.094 m (Figure 2). The cave was a square with a side length of 1 m. The roof of the model was regarded as an ideal elastic body without plastic failure. Therefore, the plastic zone range and permeability changes of the roof were not analyzed in the numerical simulation analysis. At the same time, the hydraulic flushing with the same radius was simulated to compare the permeability enhancement range.

In the model, the vertical stress of 7 MPa was applied on the top of the roof, and the roll support was applied on the left boundary, right boundary, and the bottom of the model. The basic parameters for numerical simulation were shown in Table 1. The simulation related parameters were partly from actual measurements by the authors, and the other part refers to the relevant parameter test data provided by the information section of Xuehu mine.

The range of the plastic zone and the permeability enhancement zone under two different technical conditions would be presented according to the simulation results. The coal sample scanning of the plastic zone and the elastic zone in the laboratory proves that the actual microstructure of the coal body in different areas and the development of the fracture would reflect the change of the permeability of different areas of the coal seam.

### Table 1 | Numerical simulation parameters

| Parameter type | Parameter | Value |
|----------------|-----------|-------|
| Roof Elastic modulus ($E_R$, GPa) | 4.5 | |
| Poisson's ratio ($\nu_R$) | 0.28 | |
| Hard coal Elastic modulus ($E_H$, GPa) | 3.5 | |
| Poisson's ratio ($\nu_H$) | 0.3 | |
| Initial cohesion ($c_{H0}$, MPa) | 0.8 | |
| Residual cohesion ($c_{Hw}$, MPa) | 0.6 | |
| Friction angle ($\phi_{Hc}$) | 26 | |
| Initial permeability ($k_0$, $m^2$) | $4 \times 10^{-16}$ | |
| Density ($\rho_H$, t/m$^3$) | 1400 | |
| Soft coal Elastic modulus ($E_S$, GPa) | 1.5 | |
| Poisson's ratio ($\nu_S$) | 0.3 | |
| Initial cohesion ($c_{S0}$, MPa) | 0.6 | |
| Residual cohesion ($c_{Sw}$, MPa) | 0.4 | |
| Friction angle ($\phi_{Sc}$) | 25 | |
| Initial permeability ($k_0$, $m^2$) | $1 \times 10^{-16}$ | |
| Density ($\rho_S$, t/m$^3$) | 1450 | |
| Gas Cleat volume compressibility ($a$, MPa$^{-1}$) | 0.15 | |
| Jump coefficient of permeability ($\xi$) | 30 | |
| Other Equivalent plastic shear strain of coal mass ($\gamma^{pl}$) | 0.01 | |

2.3 | **Results and analysis**

The elastic-plastic zone and permeability enhancement zone of hydraulic caving, hydraulic flushing with the same diameter as hydraulic caving, ordinary cross-borehole extraction were numerically simulated and analyzed. The cylindrical coal samples of 50 × 100 mm were collected and produced from different locations in the field with hydraulic caving of Xuehu mine. A CT equipment named Phoenix V intome | x m was used to scan and observe the fracture development degree of each coal sample.

The observation results of coal sample have shown in Figure 3. Five fractures of 4-8 mm in length in the plastic zone of soft coal can be seen in Figure 3(A), and some of them have been penetrated. As shown in Figure 3(B), one main fracture with length of about 8 mm and two fractures with length of 2 and 4 mm can be observed in the plastic zone of hard coal, respectively. None of fractures were observed in the elastic zone of soft and hard coal in Figure 3(C,D).
coal and hard coal by hydraulic caving was 1.09 and 1.03 times of that by hydraulic flushing. The maximum distance from center of cross-borehole of plastic softening zone in soft coal and hard coal by hydraulic caving was 1.17 and 1.05 times of that by hydraulic flushing. The plastic failure zone of soft coal was larger than that of hard coal, and the
plastic softening zone of soft coal was larger than that of hard coal.

The area, where the permeability is greater than the initial permeability, was defined as the permeability enhancement zone. As shown in Figure 3(G,H), it can be seen that the law of distribution of permeability enhancement zone was consistent with that of plastic zone. The maximum distance from center of cross-borehole of permeability enhancement zone in soft coal and hard coal by hydraulic caving was 1.17 and 1.05 times of that by hydraulic flushing. In this model, the permeability enhancement zone of soft coal is larger than that of hard coal. In Figure 3(E), the upper coal mass of cave was still an elastic zone because it is not destroyed by shear and tension. However, the coal mass in this area was complete pressure relief and the porosity of coal mass increased, which leads to the permeability enhancement. Therefore, this zone was the elastic zone and also the permeability enhancement zone.

The higher the degree of fracture develops, the higher the permeability of the coal is and the easier the gas extraction. For coal seams with single strength, hydraulic caving and hydraulic flushing can reduce the time of gas extraction, and achieve the goal of rapid outburst elimination. But in the coal seam with soft and hard coal interbeds, the strength and resistance to flushing of soft coal and hard coal are different. So far, compared with other hydraulic methods, hydraulic caving can avoid this shortage because it can achieve better permeability enhancement effect in less time and workload.

### Table 2: Comparison of numerical simulation results

| Different maximum distances | Coal property | Hydraulic caving (m) | Hydraulic flushing (m) | Hydraulic caving flushing ratio |
|-----------------------------|---------------|----------------------|------------------------|-------------------------------|
| The maximum distance from center in plastic damage zone | Soft coal     | 4.7                  | 4.3                    | 1.09                          |
|                             | Hard coal     | 3.8                  | 3.7                    | 1.03                          |
| The maximum distance from center plastic in softening zone | Soft coal     | 5.6                  | 4.8                    | 1.17                          |
|                             | Hard coal     | 4.2                  | 4.0                    | 1.05                          |
| The maximum distance from center in the permeability enhancement zone | Soft coal     | 5.6                  | 4.8                    | 1.17                          |
|                             | Hard coal     | 4.2                  | 4.0                    | 1.05                          |

### Figure 4: Drawing of hydraulic caving implementation and equipment
3 TECHNOLOGICAL PROCESS OF CROSS-BOREHOLE HYDRAULIC CAVING TECHNIQUE

3.1 The main devices of the hydraulic caving system

Hydraulic caving system includes that (Figure 4):

1. The drilling rig, which provides power for drilling and hydraulic caving by using track movement and working in hydraulic mode.
2. The pressure device, which provides high-pressure water source for hydraulic caving, including high-pressure emulsion pump and water container.
3. The control devices, which controls and monitors water pressure and flow.
4. The high-pressure water supply device includes high-pressure sealed drill pipe, high-pressure pipeline, and high-pressure dynamic seal rotary joint.
5. The high-low pressure water jet conversion device, which is used for discharging coal under low pressure during drilling and flushing coal under high pressure during hydraulic caving.

3.2 The process of the hydraulic caving

Hydraulic caving in coal seam with a soft layer at the bottom, as a new method of eliminating outburst in soft-hard interbedded coal seam, includes prediction stage, design stage, implementation stage, effect test stage, and effect verification stage (Figure 5).

3.2.1 Step 1: Prediction stage

Before hydraulic caving, the original gas content, the original gas pressure, and the thickness of soft and hard coal in a coal seam in test area need to be predicted. The gas occurrence conditions need to be determined, and the difficulty of gas extraction needs to be assessed.

3.2.2 Step 2: Design stage

It is necessary to test and determine the cave parameters, distance between boreholes and implementation parameters. The cave parameters include the height of the cave and the amount of coal flushed out, which can be determined by observing the thickness of soft coal and the stability of the cave in the test area. The distance between boreholes is determined by the effective extraction radius of hydraulic caving cross-boreholes. The effective extraction radius of hydraulic caving boreholes is determined by pressure reduction method in the test area: Firstly, observation boreholes are drilled, the boreholes are sealed, and pressure gauges are installed at the boreholes after drilling. Secondly, hydraulic caving boreholes are drilled and caved when the pressure in the observation boreholes is stable, and the boreholes are sealed and pumped continuously. Thirdly, the pressure change in the observation boreholes is monitored. When the pressure in an observation hole decreases to 0.74 MPa, the distance between this observation hole and the centerline of...
the corresponding hydraulic caving borehole is the effective extraction radius of the hydraulic caving borehole during this extraction period. In order to avoid the interaction between observation holes, only one observation hole is arranged on each side of each hydraulic caving borehole. The arrangement of boreholes is shown in Figure 6. T1-T4 is hydraulic caving boreholes, and M1-M8 is observation boreholes. The implementation parameters are determined according to the performance of the equipment.

### 3.2.3 Step 3: Implementation stage

Hydraulic caving system can switch high- and low-pressure water flow by using a pressure controller. The specific process is as follows. Firstly, the equipment of hydraulic caving system is assembled, and boreholes are drilled. At this time, low-pressure water is used to remove drilling cuttings in boreholes. During the process, the position and thickness of soft coal are further determined. Secondly, when a drill pipe through the coal seam, it stops drilling and retreats the drill bit to the position of soft coal. Low-pressure water is switched to high-pressure water, and water emits from water jet bit. The coal mass in the soft coal seam is flushed out, and caves are formed. Thirdly, after the completion of caving, the method of “one block and one injection” is adopted to plug the boreholes immediately (Figure 7). Synthetic resin is used to plug the hole, and the length of it is 3 m. Then, the cement slurry is fed into the input tube by grouting pump. When the cement slurry flows out from gas extraction tube, the grouting is stopped. The fractures in the sealing section of boreholes can be effectively sealed because of the self-weight of the slurry. The deepest position of sealing is at the coal-rock

**FIGURE 7** Diagram of “One Block and One Injection” sealing of borehole

**FIGURE 8** (A) Location of Xuehu Coal Mine (B) Structural sketch of Xuehu Coal Mine (C) Generalized stratigraphy of 2306 working face (D) Roadway layout of 2306 working face. Location of the 2306 working face
junction. When the cement slurry is fully solidified (about 8 hours), the extraction process begins after boreholes are connected to the extraction pipeline.

### 3.2.4 Step 4: Effect test stage

The residual gas content and residual gas pressure in the extraction area are measured. When the residual gas content is <8 m³/t and the residual gas pressure is <0.74 MPa, it meets the requirements of *Provisions of the Prevention of Coal and Gas*. The coal roadway can be excavated.

### 3.2.5 Step 5: Effect verification stage

In the process of roadway excavation, a test verification is carried out for each 50 m. When the initial velocity of gas emissions in borehole \( q \) is <5 L/min and the amount of drilling cuttings \( S \) is <6 kg/m, it meets the requirements of the guidelines in *Provisions of the Prevention of Coal and Gas* in China. The coal roadway will continue to be excavated. Otherwise, the excavation will be stopped and the extraction time will be increased.

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**FIGURE 9** Observation results of caves with different amounts of coal flushed out. A, Peper; (B) the amount of coal flushed out of 0 t/m; (C) the amount of coal flushed out of 0.74 t/m; (D) the amount of coal flushed out of 1.15 t/m (E) the amount of coal flushed out of 1.54 t/m; and (F) the amount of coal flushed out of 1.93 t/m.

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4 | FIELD TEST AND APPLICATION

### 4.1 Situation of the test site

The Xuehu coal mine is located in the Yongxia coalfield in Henan Province, China. As shown in Figure 8(A), the mine is a single coal seam mining. The II-2 coal seam in the middle and lower part of Shanxi Formation of Carboniferous-Permian is the coal seam of the mine, and single seam mining is adopted. The average coal thickness of 2306 working face is 2.8 m. The gas content is 6.15-19.71 m³/t, and the gas pressure is 0.82-3.23 MPa. The upper part of the coal seam is 2 m thick hard coal, and the coefficient of firmness is 0.54-0.7. The lower part is 0.8 m soft coal, and the coefficient of firmness is 0.25-0.46. The density is 1.42 t/m³. The permeability coefficient of coal seam is 0.004129-0.083835 m²/(MPa²·d), which belongs to low permeability coal seam. Although the method of pre-drainage gas by cross-boreholes was adopted in this mine, ordinary boreholes also have shortcomings (such as small effective extraction radius, fast attenuation of gas concentration in boreholes, and less extraction amount; low extraction efficiency and high gas emission during coal
QIN et al. (2019) noted that the method of gas extraction by ordinary cross-boreholes cannot effectively solve the problem of coal and gas outburst in the process of coal roadway excavation. Aiming to the risk of coal and gas outburst mine during coal roadway excavation in Xuehu Coal Mine, a novel cross-borehole hydraulic caving technique is proposed to prevent coal and gas outburst, so as to achieve the goal of safe and efficient excavation.

Aiming to the risk of coal and gas outburst mine during coal roadway excavation in Xuehu Coal Mine, a novel cross-borehole hydraulic caving technique is proposed to prevent coal and gas outburst, so as to achieve the goal of safe and efficient excavation.

The test site is located at the 2306 transportation roadway and the 2306 low located drainage roadway. The two roadways are located in the eastern part of the minefield, as shown in Figure 8(B,D), the thickness of hard and soft coal, and the lithology and thickness of roof and floor are shown in the Figure 8(C); the original gas content is 13.6 m³/t. The height of the cave is determined to be 0.8 m. The caves with the amount of coal flushed out of 0, 0.74, 1.15, 1.54, and 1.93 t/m are implemented in coal seam (t/m refers to the flushing amount of per unit length of borehole in soft coal). The stability of caves is observed at the coal-rock junction with a peeper. As shown in Figure 9, the boreholes with the amount of coal flushed out of 0, 0.74, and 1.15 t/m were complete, the borehole with the amount of coal flushed out of 1.54 t/m collapse, and the borehole with 1.93 t/m coal-washed volume collapsed more seriously. Therefore, in order to prevent borehole blockage by cross-borehole collapse,
extraction efficiency was reduced. At the same time, the more coal flushed, the larger the permeability range, the amount of coal flushed out of 1.15 t/m was determined.

According to Provisions of the Prevention of Coal and Gas, the control range of the method of predraining gas in coal seam by cross-boreholes was at least 15 m outside the outline of both sides of the roadway. The effective extraction radius of caving boreholes was determined by pressure reduction method. A row of cross-boreholes was arranged every 5 m in 2306 low located drainage roadway, each row included 7 drilling holes, as shown in Figure 10. The diameter of the boreholes was 94 mm. All boreholes were made by hydraulic caving. The flushing pressure of the water jet was 42 MPa, and the caves with the amount of coal flushed out were 1.15 t/m. Figure 11 was a coal storage tank for estimating the amount of coal flushed out. The detailed parameters of boreholes were shown in Table 3. A total of 20 rows of hydraulic caving boreholes were arranged. According to the same parameters, 20 rows of ordinary cross-boreholes were arranged in 2306 low located drainage roadway to compare coal and gas outbursts outburst prevention effect. The boreholes were sealed and pumped immediately after the completion of hydraulic caving, and the negative pressure of extraction was 18 KPa. The extraction parameters were recorded daily, including negative pressure, mixed volume, concentration, and so on.

### Table 3  Implementing parameters of cross-boreholes

| The number of boreholes | The length of bore-hole (m) | The angle of bore-holes (°) | The thickness of hard/soft coal (m/m) | the amount of coal flushed out (t/m) |
|-------------------------|-----------------------------|-----------------------------|---------------------------------------|-----------------------------------|
| 1#                      | 21.4                        | 107                         | 2/0.8                                 | 1.15                              |
| 2#                      | 19.2                        | 83                          |                                       |                                   |
| 3#                      | 21.6                        | 59                          |                                       |                                   |
| 4#                      | 27.5                        | 41                          |                                       |                                   |
| 5#                      | 35.2                        | 30                          |                                       |                                   |
| 6#                      | 44                          | 22                          |                                       |                                   |
| 7#                      | 53.2                        | 17                          |                                       |                                   |

**Figure 11** Coal storage tank

**4.2 | Results and discussion**

In the process of hydraulic caving, a lot of gas and gas-bearing coal were discharged from boreholes with high pressure water, which reduced the burden of extraction. The diameter of cave discovered during the tunnel excavation can reach 1 m, which was about 11.2 times larger than that of common boreholes. After hydraulic caving, the pressure relief range and permeability of coal around boreholes were improved, and the amount of extraction and concentration of methane were increased.

Figure 12 shows that the average initial extraction concentration of hydraulic caving boreholes and ordinary boreholes is 98% and 90%. Within 180 days of extraction, the average extraction concentration of hydraulic caving boreholes is 1.09-4.1 times that of ordinary boreholes, and the average is 2.52 times. The average gas extraction concentration of hydraulic caving boreholes decreases to 33.7% in 180 days and that of ordinary boreholes decreases to 5.6% in 180 days. It can be seen that the reduction rate of the average extraction concentration of ordinary boreholes is much faster than that of hydraulic caving boreholes.

Figure 13 shows that the initial flow of average single hydraulic caving borehole and ordinary borehole is 0.0108 m³/min and 0.00592 m³/min. Within 180 days of extraction, the flow of average single hydraulic caving boreholes was 1.34-12.9 times that of ordinary boreholes, and the average was 5.34 times. In the first 20 days of extraction, the average single borehole flow of ordinary borehole had decreased sharply to 12.2% of the initial value and that of hydraulic caving boreholes had decreased to 60% of the initial value and the reduction rate was <1/5 of that of ordinary boreholes. The flow of average single hydraulic caving boreholes decreases to 3.3% in 180 days and that of ordinary boreholes decreases to 1.6% in 180 days. It can be seen that the average single borehole extraction flow of hydraulic caving boreholes was larger than that of ordinary boreholes in 180 days.

At the same time, the residual gas content in the test area was measured every 10 days. The residual gas content in the test area of hydraulic caving boreholes had decreased to
8 m$^3$/t after 110 days of extraction. By contrast, the residual gas content in the test area of ordinary boreholes was higher than 12.4 m$^3$/t in 180 days, which was far from the goal of eliminating coal and gas outburst.

The implementation time and the extraction amount in 180 days of hydraulic flushing boreholes, hydraulic caving boreholes, and ordinary boreholes were compared through field investigation and statistical analysis. As shown in Figure 14, it can be seen that the effective extraction radius of hydraulic caving boreholes was 5 m, which was slightly larger than that of hydraulic flushing (4.8 m) in 180 days. The effective extraction radius of two methods was 4 times that of ordinary boreholes. The implementation time of single hydraulic caving borehole was 180 minutes, which was 1.5 times longer than that of single ordinary borehole (120 minutes) and 1/2 longer than that of single hydraulic flushing borehole (360 minutes). The average amount of single borehole of hydraulic caving for 180 days was 566.8 m$^3$, which was 6.06 times that of single ordinary borehole (93.5 m$^3$) and basically the same as that of hydraulic flushing borehole(550.6 m$^3$). When the extraction efficiency of hydraulic caving boreholes and hydraulic punching boreholes were the same, the workload and implementation time of hydraulic caving boreholes were far less than those of hydraulic flushing. Although hydraulic caving boreholes took 60 minutes longer than ordinary boreholes, the extraction efficiency was...
much higher than that of ordinary boreholes in the same extraction time.

In order to verify the effect of hydraulic caving in coal seam with a soft layer in eliminating coal and gas outburst, the effect was verified every 5 m of roadway excavation in the 100 m coal roadway in the test area of hydraulic caving. The residual gas content was determined again. The validation index was $q$ and $S$. When $q$ and $S$ was $<5$ m$^3$/min and 6 kg/m, the effect was verified to be qualified, and the coal roadway can be excavated normally. On the contrary, it was necessary to continue extraction. In the process of verification, $q$, $S$, and the residual content were always lower than 4 m$^3$/min, 5.4 kg/m, and 7.1 m$^3$/t. As shown in Figure 15, there were no dynamic disasters in the process of excavation, so hydraulic caving in coal seam with a soft layer can effectively eliminate coal and gas outburst.

5 | CONCLUSION

Considering the difficulty of gas drainage in coal seam with a soft layer at the bottom, a novel cross-boreholes hydraulic caving technique was proposed. The main conclusions are as follows:

1. By hydraulic caving, the scope of plastic zone around boreholes becomes larger, and the permeability of coal around boreholes is improved. The plastic zone and the permeability range of hydraulic caving are about the same as that of hydraulic flushing, which is 2.16-2.87 times as much as that of ordinary boreholes. This shows that the best extraction effect can be reached under less workload by hydraulic caving.
2. Through the CT scanning of the coal samples at different locations around boreholes, the number of fracture development is plastic zone of soft coal $>$ plastic zone of hard coal $>$ elastic zone of soft coal $=$ plastic zone of hard coal, which shows that plastic zone of soft coal has the best permeability enhancement effect by hydraulic caving.
3. The effect of hydraulic caving technique is tested in the field. Compared with ordinary drainage boreholes, the average methane concentration of boreholes using the hydraulic caving is increased by 1.09-4.1 times, and the average methane amount of single borehole is increased by 6.06 times. The fast outburst elimination of coal seam is completed in the area with hydraulic caving after 110 days of extraction, and $Q$ and $S$ values are in normal range during roadway excavation. These results indicate that this novel cross-borehole hydraulic caving technique in coal seam with a soft layer is an effective means to improve the efficiency of gas extraction and fast eliminate the coal and gas outburst.

ACKNOWLEDGMENTS

This research was supported by Program for Changjiang Scholars and Innovative Research Team in University [Grant Number IRT16R22]; Henan Province Industry-University-Research Cooperation Project [Grant Number 162107000040]; and China Postdoctoral Science Foundation [Grant Number 2017M622343].

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**How to cite this article:** Qin B, Wei G, Lou Z, et al. A new cross-borehole hydraulic caving technique in the coal seam with a soft layer for preventing coal and gas outbursts during coal roadway excavation. *Energy Sci Eng.* 2020;8:1120–1134. [https://doi.org/10.1002/ese3.572](https://doi.org/10.1002/ese3.572)