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Pressure Relief and Permeability Enhancement Technology of Fixed-point Hydraulic Cavitation in Low Permeability Soft Coal Seam

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Abstract

To ensure the smooth and efficient gas extraction, the technology of interval drilling fixed-point hydraulic cave-making was proposed. Taking Wuyang Coal Mine in China as the background, the influence of fixed-point hydraulic cave-making by multihole interval on the pressure relief effect of soft coal seams was analyzed by numerical simulation, the transform of stress in coal seam was also analyzed under the conditions of single hole and cave-making by multiaperture interval with different hole-making radius and different hole spacing. The field test scheme of fixed-point hydraulic cave-making at boreholes intervals was established, and the verification analysis of the numerical simulation was carried out. Results show that when the hole spacing is fixed at 5 m and the hole radius is 1 m, the stress disturbance covers the whole coal seam, and the pressure relief areas produced by the hole-making holes on both sides overlap with the common holes, forming a pressure relief area with better pressure relief effect between the holes. When the cavitation radius is fixed to 0.8 m, the pressure relief effect of coal seam decreases with the increase of borehole spacing, reasonable reduction of borehole spacing can effectively improve the overall pressure relief effect of coal seam. Compared with ordinary drilling, the gas drainage concentration of hole drilling is increased from 50-60% to 80-90%. The conclusions obtained in this study can provide the reference for the gas extraction engineering.

Keywords: Soft coal seam, Hydraulic cavitation, Gas extraction, Numerical simulation

1. Introduction

Coal is the main source of energy that drives the world economy. In recent years, due to the over-exploitation of coal resources, the shallow coal resources are exhausted, and the coal mining depth gradually increases, and the in-situ stress and gas pressure increase accordingly. At the same time, with the increase of buried depth, the permeability of coal seam gradually weakens, which makes it difficult to carry out gas pre-drainage, and coal and gas outburst disasters occur frequently, which increases the difficulty of safe mining in coal mines [1-4].

Coal and gas outburst is the result of the joint action of many factors such as gas pressure, crustal stress, coal properties and tectonic environment. It is a very complex dynamic phenomenon, which seriously threatens the safety mining and underground workers [5-7]. In order to prevent the occurrence of coal and gas outburst disasters and reduce the personnel and economic losses caused by gas disasters, some hydraulic permeability enhancement measures are usually used for pre-drainage of gas in coal seams. Hydraulic punching is widely used in many outburst mines because of its remarkable permeability enhancement effect and strong usability.

Therefore, it is of great significance to study the pressure relief effect of coal seam under hydraulic punching and its influence on gas pre-drainage, so as to provide the theoretical basis for coal seam gas pre-drainage and ensure coal mine safety mining.

2. State of the art

In-depth research on the mechanism of coal and gas outburst can provide a reliable reference for the prevention and control of coal and gas outburst disasters. Further understanding of the mechanism and influencing factors of coal and gas outburst is crucial for the prevention and control of coal and gas outburst. Bondarenko et al. studied the affect of natural gas hydrate decomposition in coal and gas outburst [8, 9]. Shadrin & Diyuk defined the geomechanics criterion of local outburst of coal seam [10]. Voitenko & Kovtunet tested the applicability of brittle fracture criterion in predicting large-scal
e coal and gas outburst under compressive loads [11]. Wold et al. analyzed the influence of spatial variability of coal seam parameters on coal and gas outburst during mining [12]. Nie & Li considered that vibration is the most important factor inducing coal and gas outburst, and analyzed the influence mechanism of vibration on coal and gas outburst through experiments and examples [13]. Zykov & Ivanov performed theoretical research on the incipient motion conditions of sudden coal and gas outburst in coal seam broken working face, and they obtained the expression of active force and passive force gradient of sudden outburst [14]. Gao et al. discussed the four dynamic processes of coal

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and gas outburst, established a numerical model by RFPA-GAS software, and revealed the dynamic failure mechanism of coal and gas outburst in roadway with different support intensities and no support conditions [15]. Jin et al. analyzed the formation and migration mechanism of outburst gas flow, and they confirmed the promoting effect of coal powder on outburst disaster based on experiments [16]. To accurately predict the risk of coal and gas outburst under different conditions, Wang et al. constructed the forecast of outburst dangerousness indices system and risk classification index system based on extension theory [17]. Zhang et al. proposed a new coal and gas outburst prediction method by synthetically considered many factors, but its feasibility and veracity had not been verified due to the risk and uncertainty of field outburst [18]. The mechanism of coal and gas outburst can provide the evidence for the prevention and control of outburst. On this basis, reasonable measures are adopted to relieve the pressure of coal seams to further ensure the safety of coal mining projects and reduce unnecessary losses.

Hydraulic punching breaks and flushes out the coal body via by way of high-pressure water jet, forming a certain size of holes in the coal body. Under the action of ground stress, the coal around the holes moves to direction of hole drilling due to its plastic softening and expansion characteristics, produce a lot a large number of micro-fractures in the coal body, promoting gas desorption. The small cracks in the coal seam provide a migration channel for the desorption of gas, improving the efficiency of borehole gas extraction, and thus achieving the purpose of coal seam pressure relief [19-23]. Some scholars have conducted lots of research to analyze the influence of hydraulic punching on the pressure-relieving effect of coal seam. Vasyliev developed a method and equipment for pulse hydraulic punching in coal seam, which effectively prevented the generation of coal and gas outburst catastrophe [24]. Gu & Wu put forward the hydraulic punching pressure relief and reducing reflection technology, they theoretically analyzed and verified the influence of coal seam gas drainage and crack propagation under different coal output conditions [25]. Based on the low permeability and rheological properties of coal seam, Xu & Wang investigated the influence of hydraulic punching on gas drainage effect under different coal output by numerical simulation and field test [26]. Xu et al. inspected the influence of different coal output and extraction cycles of a single borehole on the extraction radius [27]. Cao et al. established the theoretical formula of the effective influence radius of gas extraction and the total amount of gas extraction [28]. Wang et al. simulated the procedure of coal seam fissure development after hydraulic punching, and they studied the impact of hydraulic punching on the distribution of crustal stress and gas pressure in coal seam [29]. As a technology of pressure relief and permeability enhancement in coal seam, hydraulic punching shows good practicability in aspect of improving coal seam permeability and gas extraction efficiency.

Some scholars have studied the stress evolution features of coal seam after multi-hole punching, analyzed the pressure-relieving effect of different punching semidiameter on coal seam, and verified the interactive effect of multi-hole punching on gas extraction in the field. Zhang et al. studied the stress evolution route, plastic failure characteristics, gas seepage, diffusion and migration characteristics of coal bedding cave-making, and they analyzed the interactive effect of multi-hole cave-making on gas drainage [30]. Wang et al. carried out numerical simulation on the pressure-relaxing effect of hydraulic hole-making in soft coal seam, and they analyzed the plastic failure zone, pressure relief zone and stress unloading path of coal around the borehole of coal bedding cave-making and cross-layer cave-making [31]. Although many studies on the stress change characteristics of coal after pressure relief were carried out, and few scholars analyze the pressure relief effect and the influence of gas drainage caused by the porous interval cave-making and different borehole distance cave-making.

Taking the engineering situation of Wuyang Coal Mine in China as the background, a numerical model was established to analyze the influence of different cave-making radius and different borehole spacing of fixed-point hydraulic cave-making in the middle of coal seam on the stress change of coal seam. The effect of this measure on gas pre-drainage was verified by the field tests. The rest of this study is organized as follows. Section 3 gives the engineering background, the numerical simulation analysis and design of field trial. Section 4 gives the results analysis and discussion, and finally, the conclusions are summarized in Section 5.

3. Methodology

3.1 Engineering background

Wuyang Coal Mine is located in the north-east Lu'an mining area, Xiangyuan County, China, with an area of about 78.36 km^2. The main coal seam of the mine is No. 3 coal seam of Shanxi Formation of Lower Permian, the thickness is 1.99-6.91 m, the average thickness is 5.54 m. It is a stable minable coal seam in the whole area, and the check & ratify production capacity is 3.0 Mt/a. Based on the tested results of gas emission in 2016, the absolute gas emission in Wuyang Coal Mine was 106.42 m^3/min, and the relative gas emission was 20.66 m^3/t, it is the high gas mine. The minefield is located between the Taishan-type faults in the middle part of the eastern wing of Qinshui coalfield, and the dip angle of strata is 4-14°. The roof and floor mainly are mudstone and sandy mudstone. The roof locally is silty sandstone or medium fine sandstone, and the floor locally is fine sandstone or silty sandstone.

The No. 3 coal seam of 8003 transport roadway in Wuyang Coal Mine has an average thickness of 5.95 m. The structure of coal seam is simple, and the local lower part contains a layer of gangue, occasionally two layers, which thickness is 0-0.80 m, generally 0.18-0.40 m, and the lithology is mudstone or carbonaceous mudstone. The roof and floor are sandy mudstone with thickness of 3.35 m and 4.7 m, respectively. The stratum sketch is shown in Fig. 1.

The punching scheme of 8003 working face was determined based on the field geological data, and the fixed-point hydraulic cave-making was made in the middle of the coal seam by the way of cross-layer drilling. The high pressure water was used to scour the middle of the coal seam to form large-scale cylindrical holes, which promoted the coal body around the borehole to move continuously to the direction of the borehole under the action of in-situ stress, resulting in the stress redistribution of the coal seam and the effect of pressure relief and permeability enhancement of the coal seam.

Stratigraphic unit				Thickness (m)		Stratigraphic column	Lithological description
System	Series	Group	segment	Depth	Total		
Quaternary	Upper	Lower stone box group		601.7	9.21		Dark gray, thick layered, dense, and contains many plant stem and leaf fossils. The port is uneven or flat, and contains a large number of muscovite flakes. The local coal seam line is partially disguised as mudstone, and the local fractures are developed without filling. The lower part is sandstone banded.
				603.42	1.72		Gray green, thin layer, mineral composition is given priority to with feldspar, quartz, followed by dark ore, with a large number of mudstone bands, local fracture development, no filling, containing more muscovite, poor sorting, subangular.
				606.77	3.35		Deep gray, thick layered, dense, flat fracture, containing more muscovite flakes, bottom with coal wire.
				612.72	5.95		Black, bright type, bright coal, vitreous luster, blocky shape, endogenous cracks.
				617.42	4.7		Deep gray - black gray, thick layered, dense, containing a large number of muscovite flakes, the upper contains more plant stems and leaves fossils, the bottom with sandstone strip, the bottom of the crack development, fracture flat.

Fig. 1. Stratum diagram of Wuyang Coal Mine.

3.2 Numerical simulation analysis

FLAC3D numerical software was used to establish a numerical model to simulate the stress changes of coal around the hole under different cave-making radius and different borehole spacing after fixed-point the hydraulic cave-making in the middle of the coal seam. The materials in the model complied with Mohr-Coulomb criterion, that is the strength of coal body consistented with the Mohr-Coulomb strength criterion:

$$|\tau| = \sigma \tan\varphi + c \tag{1}$$

where, τ is the shear stress of coal, σ is the normal water jet pressure on coal, φ is the internal friction angle of coal, c is the cohesion of coal. It can be seen from Eq. (1) that when the hydraulic punching water jet pressure exceeds the shear strength that the coal body can withstand, the coal body produces shear failure, and which is washed out of the borehole under the action of water flow, thus forming large-diameter holes in the coal body.

According to the actual geological conditions of Wuyang Coal Mine, a single-hole model with length, width and height of 15 m, 15 m, and 14 m was established. The model was divided into three layers, namely sandy mudstone (roof), original hard coal seam, and sandy mudstone (floor) from top to bottom. It was assumed that the dip angle between coal and rock strata was 0°, the thickness and mechanical parameters of each rock layer were shown in Table 1.

Table 1. The computational parameters in the model of Wuyang Coal Mine.

Name	Thickness (m)	Tensile strength (MPa)	Compressive strength (MPa)	Internal friction angle (°)	Cohesion strength (MPa)	Elastic modulus (MPa)	Density (kg/m^3)
Sandy mudstone	3.35	2.8	26.6	24	7.0	29	2500
No. 3 coal	5.95	2.1	20.0	16	1.4	14	1250
Sandy mudstone	4.70	2.8	26.6	24	7.0	29	2500

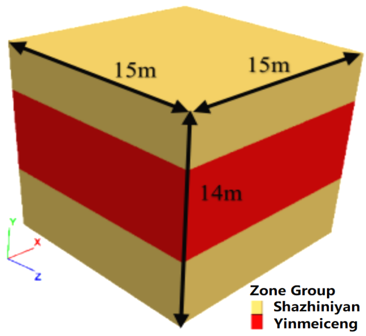
After the establishment of the model, the hydraulic cave-making work was carried out in the middle of the coal seam. The cave-making radius was set to 0.5 m, 0.8 m and 1 m, respectively. The drilling diameter of the bottom plate and the original coal seam without punching was 0.05 m. The model was surrounded by roller support, the bottom was fixed constraint. Taking account into the weight of the overlying strata, the vertical stress of 15.1 MPa was applied in the upper part, and the horizontal stress was the same as the vertical stress, that is, the coal and rock mass was in a static water state.

Firstly, the numerical model of hydraulic flushing was established, and the initial stress balance of the model was carried out. Finally, the model was calculated and the calculation results are analyzed. Model grouping and hydraulic cavitation are shown in Fig. 2. When the initial stress of the model was balanced, the drilling and cave-making of the model were carried out, and the construction sequence was ignored. In the process of simulation calculation, except for the different cave-making radius and borehole spacing, the other parameters setting and calculation process were consistent.

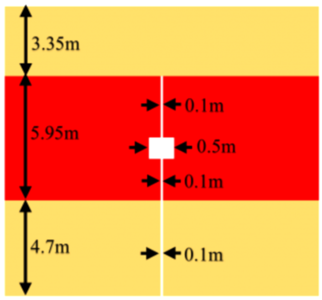
3.3 Design of field trial

The test site was within the range of 80-0305 bottom drainage roadway in Wuyang Coal Mine, the width of the roadway was 4.5 m, the height was 3.2 m, the cross-sectional area was 14.4 m^2. The coal seam was relatively soft and the structure was simple, the thickness of the coal seam was 1.99-6.91 m, the mean thickness was 5.54 m, and the firmness coefficient f was 0.27-0.44, which was suitable for hydraulic cave-making test. The roadway arrangement of the test site is shown in Fig. 3.

The drilling site of this test was the 80-0305 bottom drainage roadway. To improve the gas drainage effect of the borehole through the hydraulic hole-making of the through-layer hole in the 8003 transportation roadway, the final hole position of the borehole was within 15 m of the excavation front and the roadway contour of the 8003 transportation roadway and the 8005 return airway. The design of borehole was shown in Fig. 4. The Φ113 mm drill bit was used to construct the pre-drainage drilling through the layer. The length of the cave-making section was 1 m, and the cave-making position was located 2 m after crossing the coal seam. The plane graph of the final hole was shown in Fig. 4.



(a) The computational model



(b) Hydraulic cave-making

Fig. 2. Schematic diagram of numerical model and hydraulic cave-making.

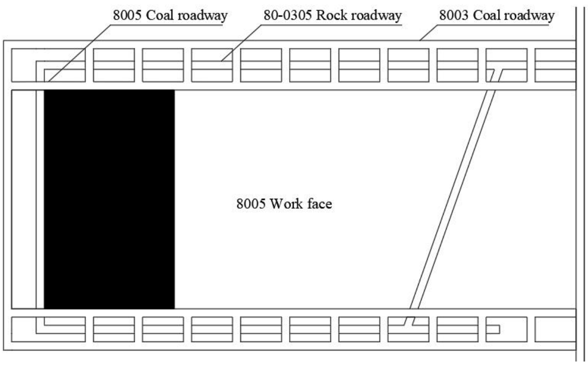
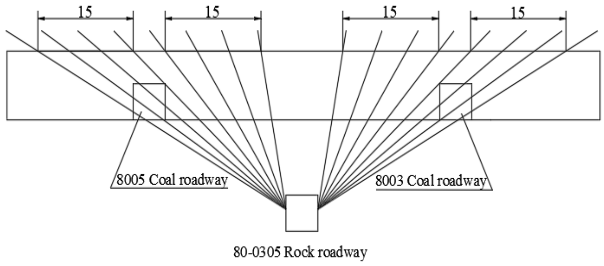
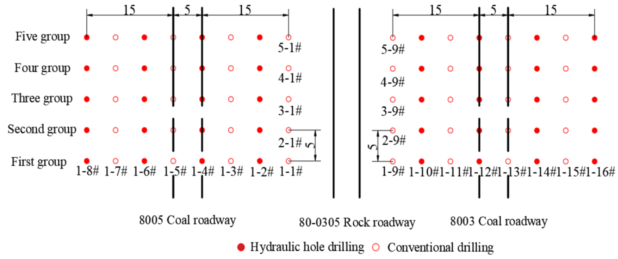


Fig. 3. The diagram of roadway layout.

During construction, first drill to the depth of the design hole, de-drill to the hydraulic cave-making position, the clear water pumping station pressurized to 15 MPa for hydraulic hole construction, and the water pressure was kept at 15-20 MPa in the process of cave making. When there was no obvious coal dust in the return water at the orifice, the drill pipe were completely withdrawn by lowering the water pressure to 3-5 MPa. A total of 5 groups of pre-pumping test boreholes were constructed from 80-0305 bottom pumping roadway to 8005 return airway and 8003 transport roadway. The number of boreholes in each group was 16, and the total number of boreholes was 80, in which the even number holes were cave-making holes and the odd number holes were common layer-piercing holes. The coal output needed to be recorded in detail in the process of drilling cave-making, and each hole-making position should take the amount of coal output by 1 m³ as the acceptance standard.



(a) Driling design The computational model



(b) Layout of boreholes terminationl

Fig. 4. Drill hole design and layout of final holes.

4. Results analysis and discussion

4.1 Stress variation of single hole with different cave-making radius

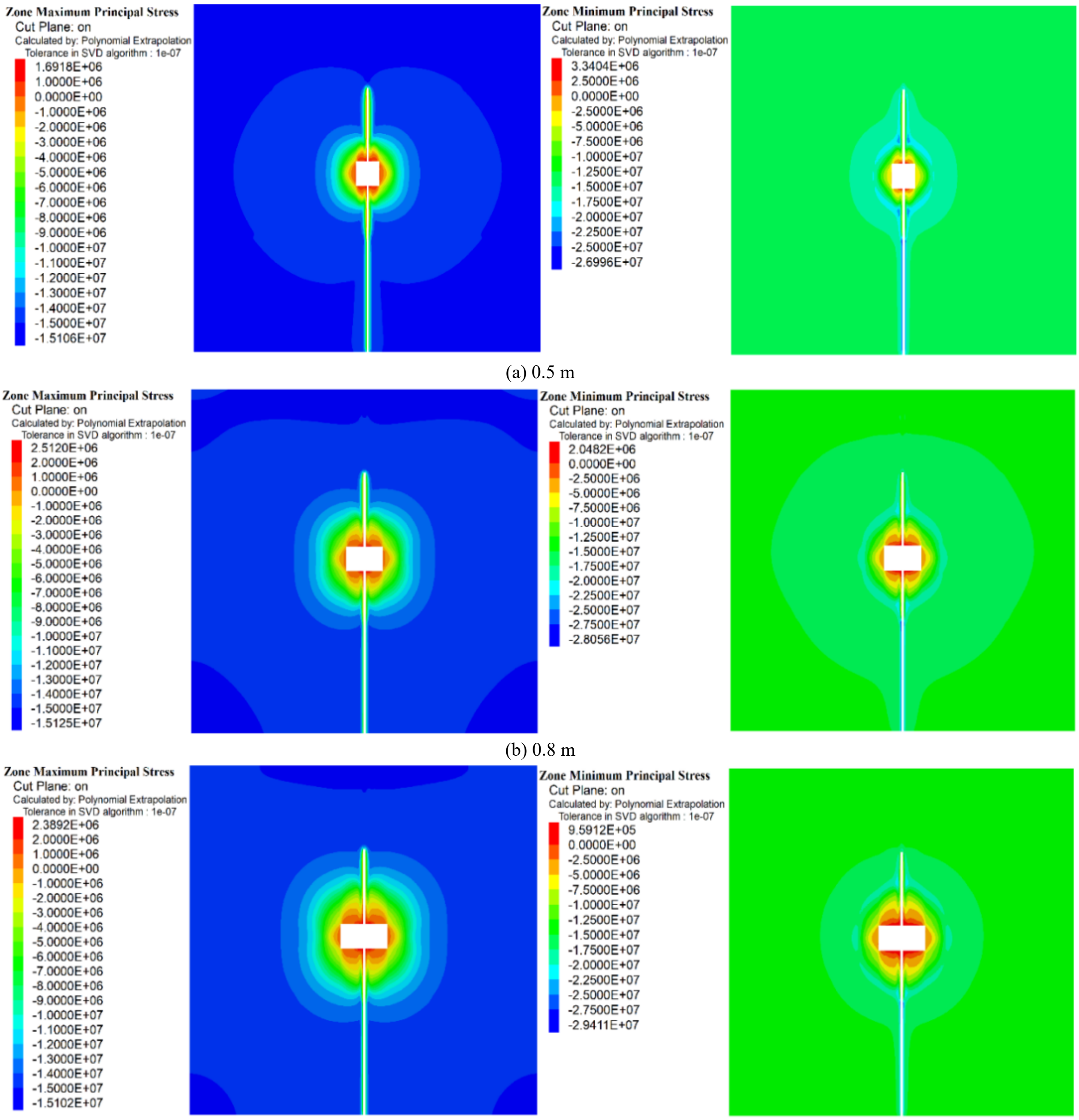
FLAC3D numerical software was used to model the cave-making in coal seam and analyze the stress change conditions of coal seam after cave-making. The numerical simulation results are shown in Fig. 5.

In the middle of the coal seam, a large cavity area was formed after hydraulic caving, and the stress in the coal body was reapportion. In this process, part of the coal body around the cave-making chamber changed from the compressive force area to the tensile stress zone, as shown in Fig. 5. After the completion of the hydraulic cave-making work, the coal seam around the cave-making chamber formed a pressure relief area with the cave-making chamber as the center, which was proximal circular shape. In the maximum principal stress nephogram, it can be seen that there is an obvious stress concentration regions around the pressure relief area, and this region increases with the increase of the cave-making radius.

With the stepwise disengage of coal seam stress, the coal body generated swelling strain in the direction of borehole center, and the pre-existing fracture of coal seam further extending, resulting in a large number of new micro fractures, promoting gas desorption and improving the permeability of coal seam. As can be seen from Fig. 5, the pressure relief area magnify with the increase of the radius of the cave after the completion of the hydraulic cave, and gradually extends to the direction away from the cave chamber in the shape of an approximate circle. The pressure-relaxing effect was the best that coal body near the cave chamber, and gradually weakens with the increase of distance.

4.2 Variation of stress at different radii of interval hole-making

Based on the numerical model of single-hole cave-making, the numerical model of interval cave-making porous was established to analyze the impact of cross arrangement of cave-making borehole and ordinary borehole on the pressure releasing effect of coal seam. The pitch of holes of the porous model was fixed to 5 m, and the pressure relief effect of the overall coal seam was simulated and analyzed when the hole radius separately for 0.5 m, 0.8 m, and 1 m. The results are shown in Fig. 6.

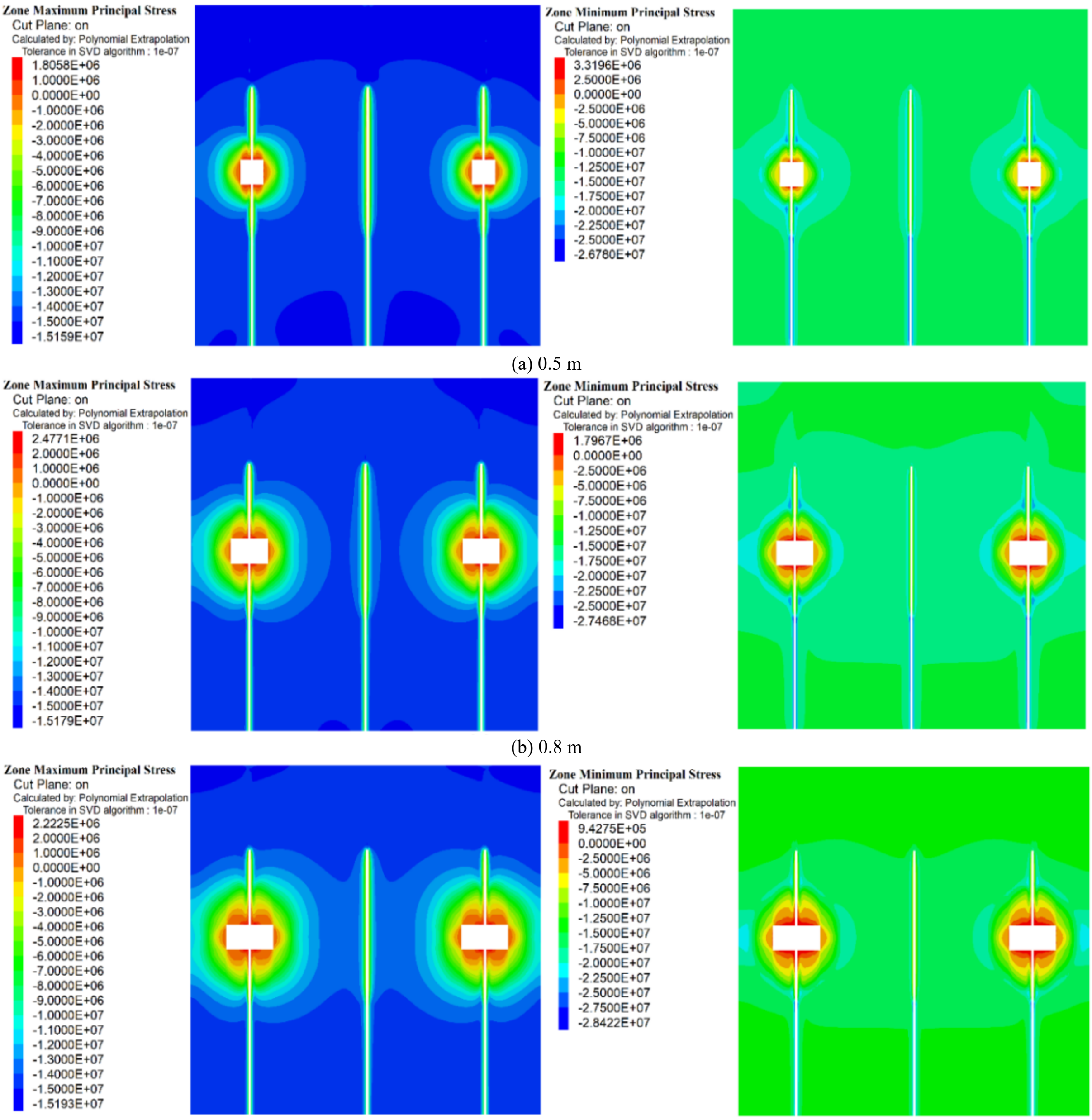


(c) 1.0 m

Fig. 5. Stress nephogram of varied cave-making radius.

As seen from Fig. 6, when the hole spacing is 5 m with the hole radius of 0.5 m, the stress disturbance caused owing to the cave-building covers the whole coal seams, but the pressure relief effect is poor. While the cave-forming radius increases from 0.5 m to 0.8 m, the pressure relief area produced by the hole-forming extends outward, which is manifested as the approximate circular layered pressure relief belt generated by the cave-forming drilling on both sides further impend the ordinary drilling in the middle. When the hole semidiameter increases to 1 m, the pressure relief area extends further outward, and the pressure relief area generated by the hole drilling on both sides is superimposed with the pressure relief area generated by the ordinary drilling, and a preferable pressure relief area is forming between the boreholes.

It can be seen from the maximum principal stress in Fig. 6 that the stress focus region is generated outside the cave-making area. When the borehole spacing is surely, the pressure relief effect of coal seam increases with the increase of the radial of the cave. With the coal body in the middle of the coal seam being flushed out, the pressure relief area in the coal body extends outward with the cave-making chamber as the center, and the closer to the cave chamber, the better the pressure relief effect can be obtained.



(c) 1.0 m

Fig. 6. Stress change of porous with different cave-making radiuses.

4.3 Stress changes of different hole spacings in interval cave-making

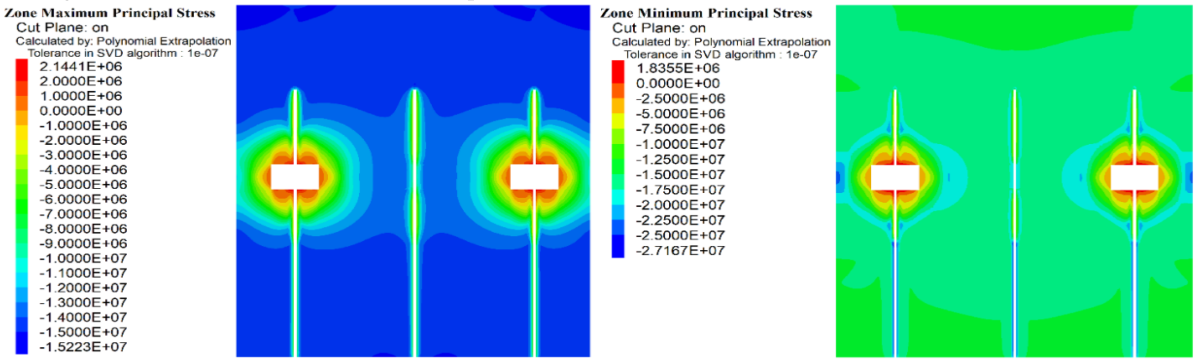
Taking the hole-making radius of 0.8 m as an example, a porous numerical model with different spacings of boreholes was established to analyze the influence of different spacings of holes on coal seam pressure relief. The hole-forming radius was fixed to 0.8 m, and the pressure relief effect of the overall coal seam was simulated and analyzed when the borehole spacing was 4 m, 5 m and 6 m, respectively. The related results are shown in Fig. 7.

It can be seen from Fig. 5 that when the cave-making radius is 0.8m, the pressure relief effect of coal body is similar to that of the drill-hole spacing of 6 m and hole-making radius of 5 m in Fig. 4, and the stress disturbance between the holes of cave-building and ordinary holes is small. With the decrease of the distance between boreholes, the pressure relief area among boreholes is close to the common borehole in the middle. When the borehole spacing is 4 m, the lamellar pressure relief area generated by the holes of cavitation on both sides is superimposed with the common borehole, and the superimposed pressure relief area is formed in the coal seam. The pressure relief effect of the overall coal seam is obvious. Therefore, when the hole radius is certain, the reasonable reduction of drill-hole spacing can effectively improve the pressure relief effect of the overall coal seam.

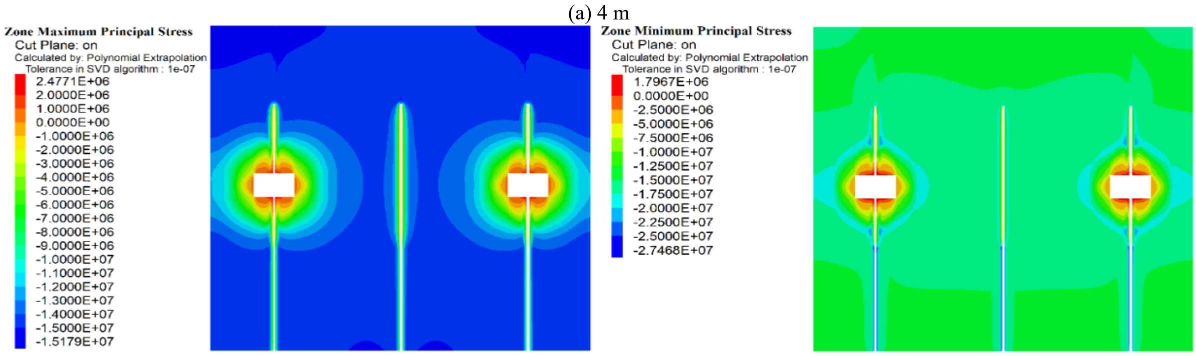
4.4 Verify and analyse of numerical simulation results by field test

According to the test scheme, hydraulic caving is carried out in 8003 transport roadway, and the concentration of gas drainage in boreholes was monitored every day after the completion of caving. When the concentration of borehole gas drainage was reduced to less than 15%, the concentration of the borehole was no longer monitored. Four cave-building boreholes and the surrounding conventional drilling were randomly selected in 8003 transport roadway to compare the gas extraction concentration. The comparison results are shown in Fig. 8.

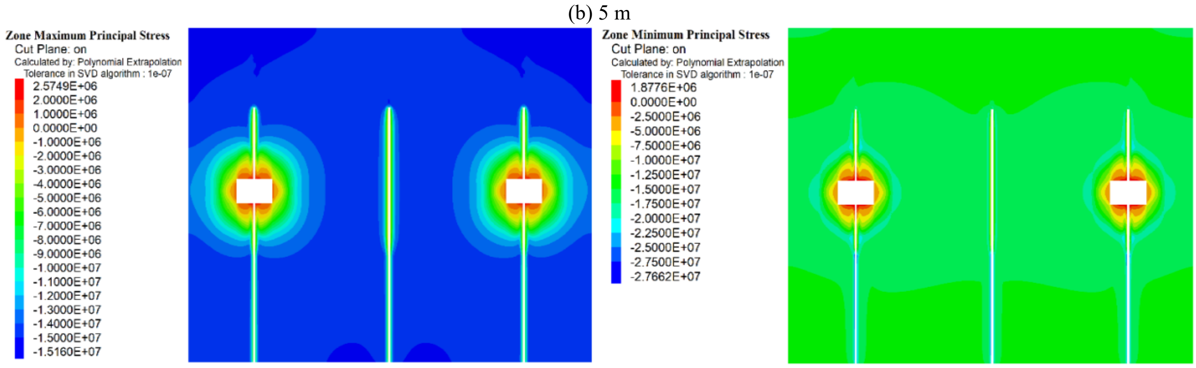
Among them, the red line represents the gas drainage concentration of ordinary boreholes, and the black line represents the gas extraction concentration of fixed-point hydraulic cavitation boreholes. As can be seen from Fig. 8, the concentration of common cross-layer drilling is 50-60%, and the concentration attenuation below 15% after 30-34 days, which is adverse to the sustaining and high efficiency extraction of gas in coal seam. After hydraulic cavitation, the gas drainage concentration reached 80-90%. Compared with conventional drilling, the daily gas drainage concentration increased by nearly twice, and the gas drainage time was effectively prolonged, which greatly enhanced the efficiency of borehole gas drainage, and was conducive to shorten the gas drainage time and realized the rapid and safety mining.



(a) 4 m

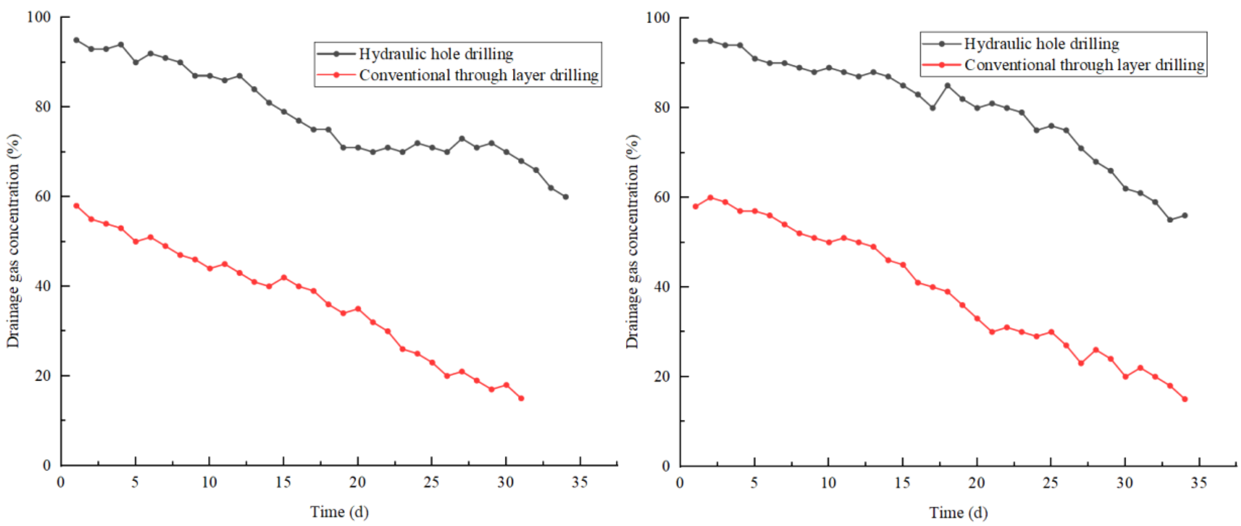


(b) 5 m



(c) 6 m

Fig. 7. Stress change of porous with different cavitation distances.



1# Contrast borehole

2# Contrast borehole

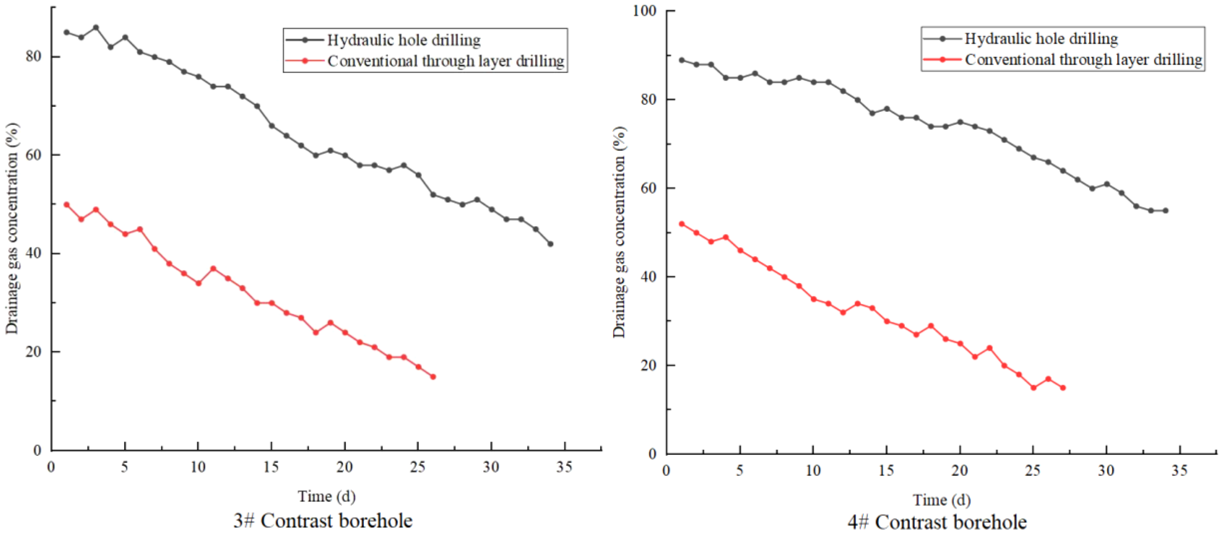


Fig. 8. Comparison of gas drainage concentration.

5. Conclusions

Aiming to the problem of poor gas drainage effect in Wuyang Coal Mine in China, the fixed-point hydraulic cave-making technology of interval drilling was proposed, and the stress change of each layer after fixed-point hydraulic caving in coal seam wa analyzed by numerical simulation. Combined with the field test to verify the results of numerical simulation, the conclusions in this study are as following:

(1) After the hydraulic cave-making in the coal seam, the pressure relief effect of the coal body nearby the cave-making area is remarkable, and the pressure relief effect attenuates with the augment of the distance from the cave-making region, and as the augment of the radius of the cave-making, the scope of the pressure relief area of the coal body is gradually expanded.

(2) When the borehole spacing is fixed, the pressure relief effect of the coal seam increases with the increase of the hole radius. With the coal body in the middle of the coal seam being washed out, the pressure relief area in the coal body extends outward with the cave chamber as the center, and the closer to the cave chamber, the better the pressure relief effect is; when the cave radius is fixed, the pressure relief effect decreases with the increase of borehole spacing. Reasonable reduction of borehole spacing can ameliorate the pressure relief effect of coal seam and improve the efficiency of gas extraction.

(3) After the fixed-point hydraulic caving in the coal seam, the gas drainage concentration increased from 50-60% of the conventional drilling to 80-90%, which is nearly doubled, effectively prolonged the drainage time, shortened the gas drainage cycle, and the risk of coal and gas outburst is reduced.

The stress change of fixed-point hole-making in soft coal seam was studied under the action of hydrostatic pressure, without considering the deformation of residual coal in coal seam under stress concentration, and the change of coal permeability under the condition of stress concentration. The evolution of permeability and deformation of coal under non-hydrostatic pressure still need to be further studied.

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