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# Study on Mechanism of Pressure Relief and Permeability Enhancement in Soft-hard Composite Coal Seam by Directional Hydraulic Flushing Technology

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## Abstract

The soft-hard composite coal seam composed of tectonic and primary structural coal has the problems, such as high gas content, high pressure, poor permeability and difficult extraction, which seriously affect the production safety in the mining. To study the evolution characteristics of pressure relief in soft-hard composite coal seam based on directional hydraulic flushing technology, taking Hudi coal mine in China as the engineering background, and the pressure relief effect of directional hydraulic flushing on 'two soft and one hard' composite coal seam was studied by theoretical analysis and numerical simulation. The stress evolution of the whole coal seam under a single hole and porous interaction of different flushing radii were analyzed. The field test of directional hydraulic flushing in tectonic soft coal seam similar to protective layer mining was conducted. Results show that when the flushing diameter is 3-4 m, the influence range of stress disturbance covers the whole coal seam, and the vertical stress relief of the primary coal seam is the largest, which provides a theoretical basis for coal seam pressure relief and permeability enhancement technology. The average daily gas extraction (ADGE) concentration has doubled, and the ADGE purity has increased from 0.03 $m^3/d$ to 1.07$m^3/d$. The target period of gas extraction is shortened from the expected 6 months to 1 month, and the average daily driving speed of coal roadway increases from 2.32 m/d to 5.37 m/d. The gas extraction efficiency is significantly improved, and the risk of gas outburst is effectively reduced, which has important theoretical and practical significance for improving the pressure relief and permeability enhancement efficiency of the soft and low permeability coal seam.

## Keywords

Soft-hard composite coal seam, directional hydraulic flushing, pressure relief, simulation, permeability.

## Introduction

As the main energy source and important industrial raw material, coal is in the main position in the Chinese energy structure. With the deep development of coal mining, deep mines generally have high ground stress, high temperature, and gas pressure problems. The risk of coal and gas outbursts increased due to increasing in-situ stress, poor permeability of coal seam, and complex geological structure (David, 1988; Pan et al., 2012; Zhang et al., 2013; Tang et al., 2018). The prevention technologies of coal and gas outburst mainly include mining protective layer and drilling and pre-draining coal seam gas. The mining protective layer is considered to be the most effective prevention technology for coal and gas outbursts (Shuyan & Fabus, 2019; Zhao et al., 2021). Since many coal seams do not have the conditions for mining protective layers, traditional measures such as reducing the drill spacing, increasing the number of holes, and extending the extraction time are adopted for soft, low permeability coal seams. Since the severe creep deformation of tectonic coal during drilling, the borehole instability and failure affect gas drainage efficiency, resulting in the gas drainage effect is not ideal, and the outburst risk cannot be eliminated in time (Sun et al., 2012; Jiang et al., 2016; Cheng et al., 2021).

Most scholars have carried out many studies on the enhanced drainage technology and have given hydraulically enhanced measures such as hydraulic slotting, hydraulic flushing, hydraulic fracturing and loose blasting (Li et al., 2016; Seyedin et al., 2019). Among them, the hydraulic flushing technology is widely used in many coal and gas outburst mines. The hydraulic flushing technology refers to the coal seam broken by high strength impact through a high-pressure water jet under the isolation of a coal pillar or rock pillar. Through the superposition of high strength impact energy, gas potential and elastic energy of the coal seam itself, the small 'outburst' of the coal seam is induced artificially, and the advanced gas release area is formed in the coal body to eliminate coal and gas outburst. Although the traditional hydraulic measures can achieve pressure relief and reflection improvement effect to some extent, they are all faced with some problems, such as small influence range, complicated construction process, long engineering cycle, large workload and high cost.

To ensure the pressure relief effect covering the whole coal seam, a large number of hydraulic flushing is needed, and the pressure relief effect is also different due to different coal seam conditions. Therefore, improving the effect of coal seam pressure relief and permeability enhancement has become the key of the research. Based on the directional hydraulic flushing technology, combined with the characteristics of tectonic coal, the directional hydraulic flushing technology suitable for soft-hard composite coal seam was proposed. The stress evolution and distribution in coal seam after flushing was analyzed by numerical simulation and theoretical analysis, and the field test proved that the technology was efficient and feasible.

## State of the art

Hydraulic flushing technology for permeability enhancement has developed rapidly in recent years. A High-speed and high-pressure water jet is used to impact and destroy the coal body, forming certain macroscopic cracks or pores in the coal seam so that various cracks and pores of the coal body can expand, connect, or even rupture rapidly to unload the in-situ stress and increase the permeability of the coal seam (Huang 2010; Yang et al., 2017; Jiang et al., 2018). As a strengthening measure for pressure relief in the coal seam, the hydraulic flushing technology has achieved a good gas disaster prevention effect in soft and low permeability coal seams. Some scholars have done many researches on hydraulic flushing technology based on field experiments. Liu et al. (2005) analyzed the outburst prevention mechanism of hydraulic flushing, considering its application in the severely outburst coal seam. Wang et al. (2020) used the field monitoring method to study the dynamic evolution of stress and gas fields around the hole formed by the hydraulic flushing, and they found that the stress and seepage fields around the hole had obvious temporal and spatial evolution correlation. Wei et al. (2010) measured the effective pressure relief range of the hydraulic flushing by flow and pressure methods. Shen et al. (2018) established an electromagnetic radiation experimental system for the hydraulic flushing in the coal seam. According to the electromagnetic radiation characteristics of coal in the process of hydraulic flushing, they measured the effective pressure relief range and proposed the method of evaluating the pressure relief effect of the hydraulic flushing. Wang et al. (2013) studied the evolution of coal permeability near the hydraulic flushing by using RFPA2D-Flow software; combining with the field measurement data, they found that the coal permeability is related to the distribution of the main coal stress.

Among many factors affecting hydraulic flushing efficiency, the physical and mechanical properties of coal are the key factors. Some studies show that the influence range of the hydraulic flushing is small, and the hole size formed by the hydraulic flushing in a coal seam is limited by water jet pressure and coal quality. Zhang et al. (2019) revealed the pressure relief and permeability enhancement mechanism of single-hole hydraulic flushing in the composite coal seam. Li et al. (2014) proposed the construction method and principle of hydraulic flushing based on the hydraulic punching of soft coal seam by the kilometre drilling rig. Feng et al. (2017) developed a high-pressure punching physical experimental device, which could simulate the pressure relief effect of the hydraulic flushing under different in-situ stress states. Shen et al. (2015) established a three-dimensional seepage model based on FLAC$^{3D}$ to study the changes in stress, permeability and pore pressure of coal around the hydraulic flushing borehole. Chen et al. (2020) established a multi-field coupling model and analyzed the pressure relief and permeability enhancement mechanism of the hydraulic flushing in the low permeability coal seam. Hydraulic flushing is a kind of permeability enhancement technology suitable for soft and low permeability coal seam, but there are few theoretical studies on the directional hydraulic flushing of extremely thin and soft layers in a soft-hard composite coal seam.

The hydraulic flushing technology is mostly constructed by layer-through boreholes, but the construction period is long and complicated, and the reliable test result cannot be obtained in a short time. Therefore, numerical simulation methods are mostly used for the preliminary theoretical research of hydraulic flushing (Godec et al., 2021). Hao et al. (2016) established a relevant numerical model based on the rheological properties of coal, and they studied the variation and influence range of the hydraulic flushing hole diameter. Liu et al. (2021) established a coupled gas flow-geomechanics model based on an equivalent fractured-coal model to study the influence of borehole diameter on stress, plastic zone, permeability and gas pressure distribution. The multi-field coupling model was established based on COMSOL software, and the pressure relief range and gas drainage effect of the hydraulic flushing were studied under different conditions (Kong et al., 2016; Wang et al., 2017; Zhang et al., 2019; Cao et al., 2021). The numerical simulation in the research mentioned above was performed on a single hydraulic flushing model, and the interaction among the punching holes in the whole coal seam was not considered. So the effect of the hydraulic flushing and pressure relief on the whole coal seam should be further researched.

Based on the engineering background of the soft-hard composite coal seam in the Hudi coal mine, according to the good pressure relief and permeability enhancement effect of the protective layer mining, the directional water jet was sent to the structural soft coal seam, and the directional water jet running in the direction of the coal seam was used to realize the efficient directional long-distance washing and mining of the soft-hard composite coal seam. Therefore, the technology of directional hydraulic flushing for pressure relief and permeability enhancement in soft-hard composite coal seam was put forward. The pressure relief and permeability enhancement mechanism was studied by theoretical and numerical simulation, and the pressure relief effect of the interaction among multiple punching holes on the whole coal seam was analyzed. The field experiment proved that the directional hydraulic flushing technology can effectively solve the difficult extraction problem of the soft-hard composite coal seam, which provides a new theoretical method for the safe and efficient reduction of coal and gas outburst in low-permeability coal seams.

The rest of this study is organized as follows. The relevant background and the research methods are described in Section-Materials and Methods. Then the results and discussion are given, and finally, the conclusions are summarized.

## Materials and Methods

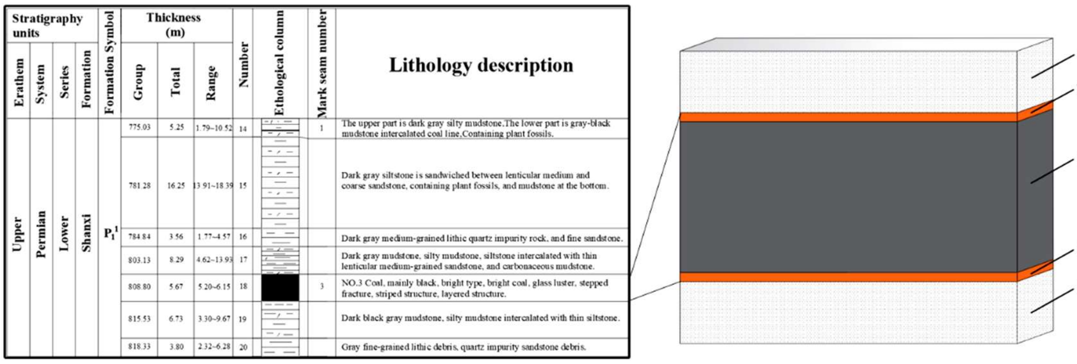
### Engineering Background

The Hudi coal mine is located in Qinshui County, Shanxi Province, China. The annual design production capacity of the mine is 0.6 Mt, belonging to the outburst coal mine. The 3# coal seam is the mainly mined coal, which is soft with poor permeability. The overall trend of the strata is northeast or nearly north-south, and the inclination tends to be northwest; the dip angle is generally less than 10°. The monoclinal structure is the main tectonic framework in the whole region, a series of wide and gentle folds are developed, and the undulation and changes of the strata and coal seams in the region are controlled and determined. Faults are not developed in the mine area, collapse columns are widely distributed, and magmatic rock intrusion is not found. The regional structure of the mine is shown in Fig. 1. The 3# coal seam is 31.7-42.3 m from the overlying K8 sandstone and 10.51-14.95 m from the K6 limestone, with a thickness of 4.52-6.15 m and an average of 5.67 m, which is a stable mineable coal seam. The 3# coal has a black-like metallic lustre, which has a striped structure with well-developed endogenous fissures, containing 1 or 2 layers of gangue with a thickness of 0.05-0.39 m.

The site of this study is at the 1305 working face of the Hudi Mine. The thickness of the coal seam along the working face is 5.20-6.15 m, with an average of 5.67 m. Affected by the bedding sliding tectonic action of the seam, the tectonic coal stratification with an average thickness of 0.3 m is formed near the roof and floor of 3# coal seam, where the structural coal layer occurs in the longitudinal direction of the coal seam. The dip angle of the coal seam is 3°-10°, with an average of 5°. The coal seam roof is silty mudstone or black mudstone, the floor is silty mudstone or greyish black mudstone, and the old bottom is siliceous mudstone.

### Theoretical Analysis

The large-scale cylindrical holes are formed in the tectonic soft coal seam by the hydraulic flushing technology. The stress state of the coal seam is secondary distributed under the influence of external disturbance and the stress state of the surrounding coal changes with the release of gas. Based on the theoretical analysis of hole mechanics, the coal around the borehole has formed the plastic and elastic zones. (Wang et al., 2016). According to the stress state with the lateral pressure coefficient of 1 in the elastic-plastic distribution of a deeplying circular tunnel, when the secondary stress state of the coal wall exceeds the yield limit of the soft coal seam, the coal rock becomes a plastic state.



| Stratigraphy units | | | | Formation Symbol | Thickness (m) | | | Number | Ethological column | Mark seam number | Lithology description |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Erathem | System | Series | Formation | | Group | Total | Range | | | | |
| Upper | Permian | Lower | Shanxi | $P_1^1$ | 775.03 | 5.25 | 1.79~10.52 | 14 | | 1 | The upper part is dark gray silty mudstone.The lower part is gray-black mudstone intercalated coal line,Containing plant fossils. |
| | | | | | 781.28 | 16.25 | 13.91~18.39 | 15 | | | Dark gray siltstone is sandwiched between lenticular medium and coarse sandstone, containing plant fossils, and mudstone at the bottom. |
| | | | | | 784.84 | 3.56 | 1.77~4.57 | 16 | | | Dark gray medium-grained lithic quartz impurity rock, and fine sandstone. |
| | | | | | 803.13 | 8.29 | 4.62~13.93 | 17 | | | Dark gray mudstone, silty mudstone, siltstone intercalated with thin lenticular medium-grained sandstone, and carbonaceous mudstone. |
| | | | | | 808.80 | 5.67 | 5.20~6.15 | 18 | | 3 | NO.3 Coal, mainly black, bright type, bright coal, glass luster, stepped fracture, striped structure, layered structure. |
| | | | | | 815.53 | 6.73 | 3.30~9.67 | 19 | | | Dark black gray mudstone, silty mudstone intercalated with thin siltstone. |
| | | | | | 818.33 | 3.80 | 2.32~6.28 | 20 | | | Gray fine-grained lithic debris, quartz impurity sandstone debris. |

*Fig. 1. The schematic diagram of rock strata and coal seam in Hudi coal mine*

It can be considered that the tangential stress is the maximum principal stress, and the radial stress is the minimum principal stress. The stress parameters in the plastic zone can be expressed by Eqs. (1) to (4) as follows:

$$\sigma_{p\theta} = \frac{\sigma_c}{\xi - 1}\left[\xi\left(\frac{r}{r_a}\right)^{\xi-1} - 1\right] \tag{1}$$

$$\sigma_{pr} = \frac{\sigma_c}{\xi - 1}\left[\left(\frac{r}{r_a}\right)^{\xi-1} - 1\right] \tag{2}$$

$$R_p = r_a\left[\frac{2\sigma_0(\xi - 1) + 2\sigma_c}{\sigma_c}\right]^{\frac{1}{\xi-1}} \tag{3}$$

$$u = r\frac{\psi(1+\mu_0)}{E}(\sigma_\theta - \sigma_r) = \frac{p_0(\xi-1)+\sigma_c}{\xi+1}\cdot\frac{2R_p^2(1+\mu_0)}{Er} \tag{4}$$

where, $\xi = \frac{1+\sin\varphi}{1-\sin\varphi}, \sigma_\theta = \frac{2C\cos\varphi}{1-\sin\varphi}$ , $\sigma_{p\theta}$ and $\sigma_{pr}$ is the tangential and radial stress in the plastic zone, $R_p$ is the radius of the plastic zone, $r_a$ is the punching radius, $\sigma_0$ is the initial stress of coal seam, $\psi$ is the modulus of plasticity, and $E_0$, $\mu_0$, $\varphi$, $C$ represents the elastic modulus, Poisson's ratio, internal friction angle and cohesion of coal, respectively. As shown in Eqs. (1) to (4), the tangential and radial stress in the plastic zone of the roadway is mainly related to the physical parameters of the coal seam, coal seam cohesion $C$ and internal friction angle $\varphi$, punching radius $r_a$ and coal seam location. The radius of the plastic zone is mainly related to the initial stress $\sigma_0$ besides the above parameters.

Combined boundary conditions for solving elastic zone:

$$\begin{cases} r = \infty, \sigma_{re} = p_0 \\ r = R_p, \sigma_{re} = \sigma_{rp} = \sigma_{R0} \end{cases}$$

The elastic region solution:

$$\sigma_{e\theta} = \sigma_0\left(1 + \frac{R_p^2}{r^2}\right) - \sigma_{R0}\frac{R_p^2}{r^2} \tag{5}$$

$$\sigma_{er} = \sigma_0\left(1 - \frac{R_p^2}{r^2}\right) + \sigma_{R0}\frac{R_p^2}{r^2} \tag{6}$$

$$u = \frac{\sigma_0(1+\mu)}{E}\left[(1-2\mu)r + \frac{R_p^2}{r}\right] - \frac{(1+\mu)\sigma_0}{E}\cdot\frac{R_p^2}{r} \tag{7}$$

where, $\sigma_{R0}$ is the radial stress at the junction of the plastic zone and elastic zone. As shown in Eqs. (5) to (7), the shear stress, radial stress and radial displacement of coal in the elastic zone are related to the initial stress but also to the radius of the plastic zone.

## Numerical Calculation Analysis

**Numerical simulation of a single borehole.** Based on the geological data, the punching scheme of the 1305 working face was determined, and the directional hydraulic flushing was carried out in the soft coal seam at the top and floor of the coal seam by the cross-seam borehole. As shown in Fig. 2, a large-size cylindrical hole was formed near the roof and floor of the coal seam, which promoted the continuous migration of the surrounding coal body to the cavity area, resulting in the secondary distribution of the stress field and the effect of pressure relief and permeability enhancement of the soft-hard composite coal seam. The FLAC$^{3D}$ numerical model was established to simulate the stress and damage of coal around the hole after hydraulic flushing of structural soft coal stratification; five groups of simulation schemes with different punching radius, including ordinary boreholes, were set up respectively. Except for different punching radius, other parameters and calculation steps of the model were consistent in the simulation process.

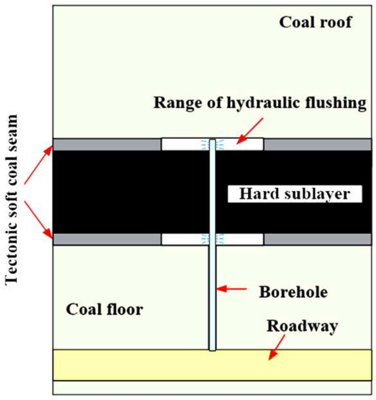


*Fig. 2. Diagram of directional hydraulic flushing technology in a tectonic soft coal seam.*

As shown in Fig. 3, the geometric model established with a punching diameter of 1 m was regarded as an example, and the length, width and height of the model were 20 m, 20 m, and 20.7 m, respectively. The model was divided into 5 layers from bottom to top, followed by bottom rock, the lower layer of tectonic coal, primary coal seam, the upper layer of tectonic coal, and roof rock, with the dip angle of coal and rock was 0°. The physical and mechanical parameters of the model are shown in Tab. 1 (Luo et al., 2017).

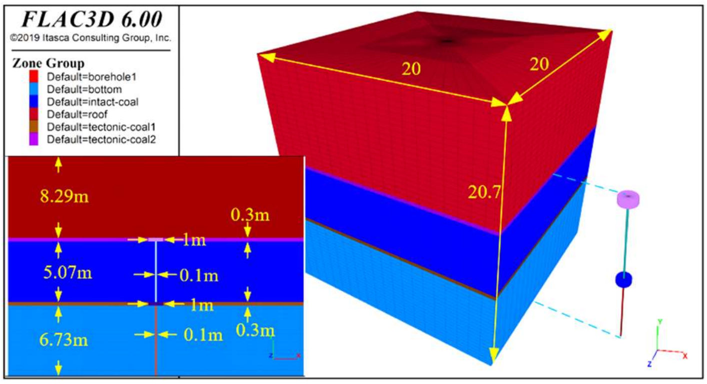


*Fig. 3. The computational model of a single borehole.*

The centre of the model was the hydraulic flushing borehole in the coal seam, and the preset tectonic coal seam punching diameters were 1 m, 2 m, 3 m, and 4 m. The drill hole diameter in the primary coal seam, the roof and the floor of coal was 0.1 m. The sliding constraint around the model was set, and the constraint boundary at the bottom was fixed. The weight of the overlying rock was considered as the vertical loading, which value was 16.5 MPa. The horizontal stress was equal to the vertical stress, so the model was in the hydrostatic stress state (Wang et al., 2014; Wang et al., 2015). The Mohr-Coulomb criterion was used in the model.

**Numerical simulation of multiple boreholes.** Based on the single punching model, the overall numerical model of multiple punching holes was established to study the stress distribution and pressure relief effect of coal seam under the combined action of multiple punching holes. As shown in Fig. 4, the hole spacing was 5 m, and four groups of simulation schemes with different punching radii of 1 m, 2 m, 3 m and 4 m were set to analyze the overall pressure relief effect and range of coal seam under different punching radius. Except for the different models, the boundary conditions and material parameters were the same as in the single borehole model.

*Tab. 1. The parameters of the model.*

| Name | Description | Height [m] | Density [kg/m$^3$] | Bulk modulus [GPa] | Shear modulus [GPa] | Internal friction angle [°] | Cohesion [MPa] | Tensile strength [MPa] |
|---|---|---|---|---|---|---|---|---|
| Roof | Charcoal grey mudstone | 8.29 | 2461 | 6.08 | 3.47 | 30 | 1.2 | 1.32 |
| Coal seam | Tectonic coal | 0.3 | 1500 | 0.326 | 0.132 | 31 | 0.83 | 0.2 |
| | Primary coal | 5.07 | 1600 | 2.18 | 1.056 | 45 | 1.67 | 0.83 |
| | Tectonic coal | 0.3 | 1500 | 0.326 | 0.132 | 31 | 0.83 | 0.2 |
| Floor | Grayish black mudstone | 6.73 | 2483 | 9.97 | 7.35 | 32 | 1.2 | 1.58 |

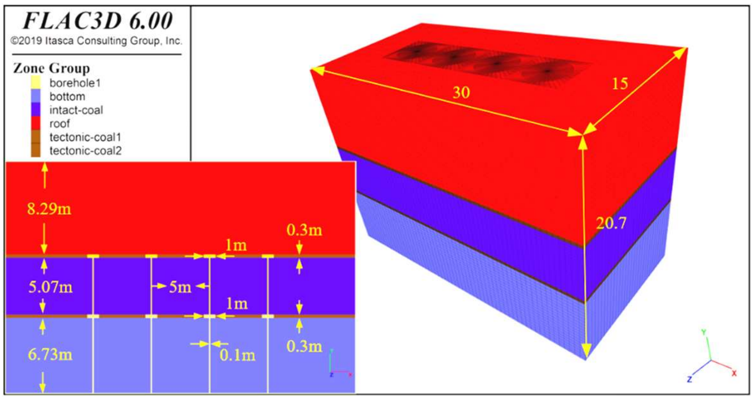


*Fig. 4. The computational model of multiple boreholes.*

## Field Test

The test site was within 120 m of the 1305 extraction rock roadway in the Hudi coal mine, and the width, height and section area of the 1305 roadway was 4.6 m, 3.5 m and 16.1 m$^2$. The thickness of the coal seam was 5.2-6.15 m, with an average of 5.7 m. There was an average thickness of 0.3 m of soft tectonic coal at the top and bottom. The fractures were fully developed, and the coal structure was broken. The consistent coefficient of primary coal and tectonic coal was 1.62 and 0.21, which was suitable for the hydraulic flushing test.

Since the first hydraulic flushing test for soft coal was conducted in Hudi Coal Mine, and there was no reliable field data for reference, a series of pre-flushing tests had been carried out. It can be seen from the test results that the effective punching radius of tectonic coal in a different place was different, and the average value of the statistical punching radius was 1.52 m. Therefore, the borehole spacing of the directional hydraulic flushing was tested according to the row spacing of 5 m. There were 144 test boreholes in total, of which 1#, 5#, 12#, 16# were punching boreholes, As shown in Fig. 5, 1# and 5# boreholes were arranged on the east side of the 1305 roadway, and 12# and 16# boreholes were arranged in the west side of the 1305 roadway, which were symmetrically distributed.

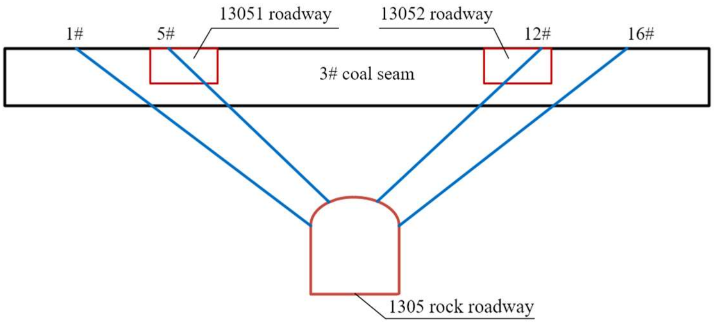


*Fig. 5. Distribution diagram of directional hydraulic flushing borehole.*

## Results and Discussion

### Analysis of Pressure Relief Effect of Single Borehole

As shown in Fig. 6, the central section of the model was used as the study surface, and the stress distribution of the coal seam around the borehole was analyzed. The maximum principal stress was the tangential stress, the minimum principal stress was the radial stress of the borehole, and the intermediate principal stress was the vertical stress. The influence range of ordinary borehole on pressure relief and permeability enhancement of soft-hard composite coal seam was small, which indirectly verified that the drainage efficiency of the ordinary borehole in the actual field was not well.

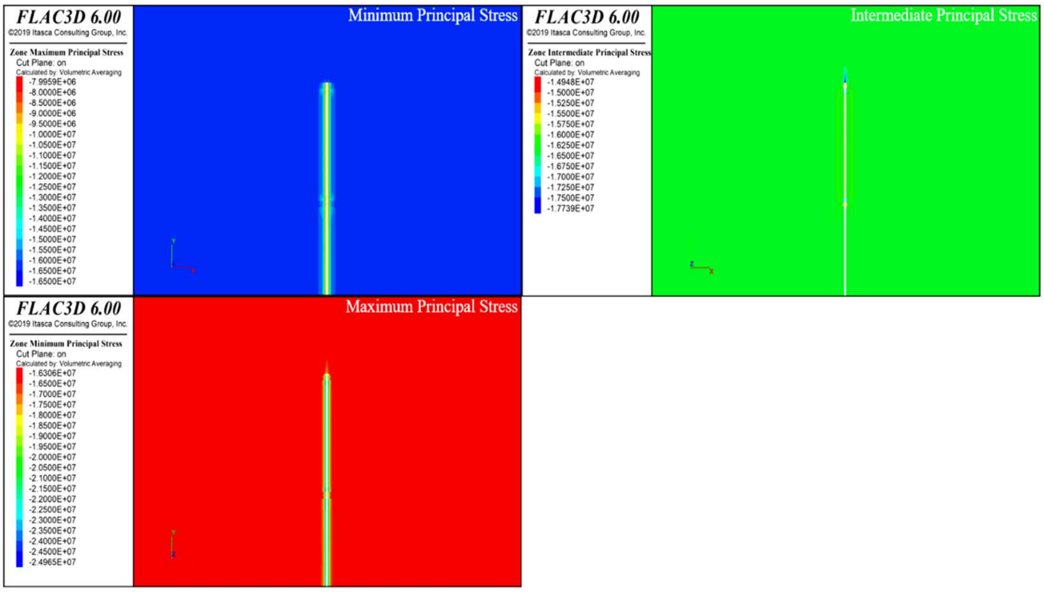
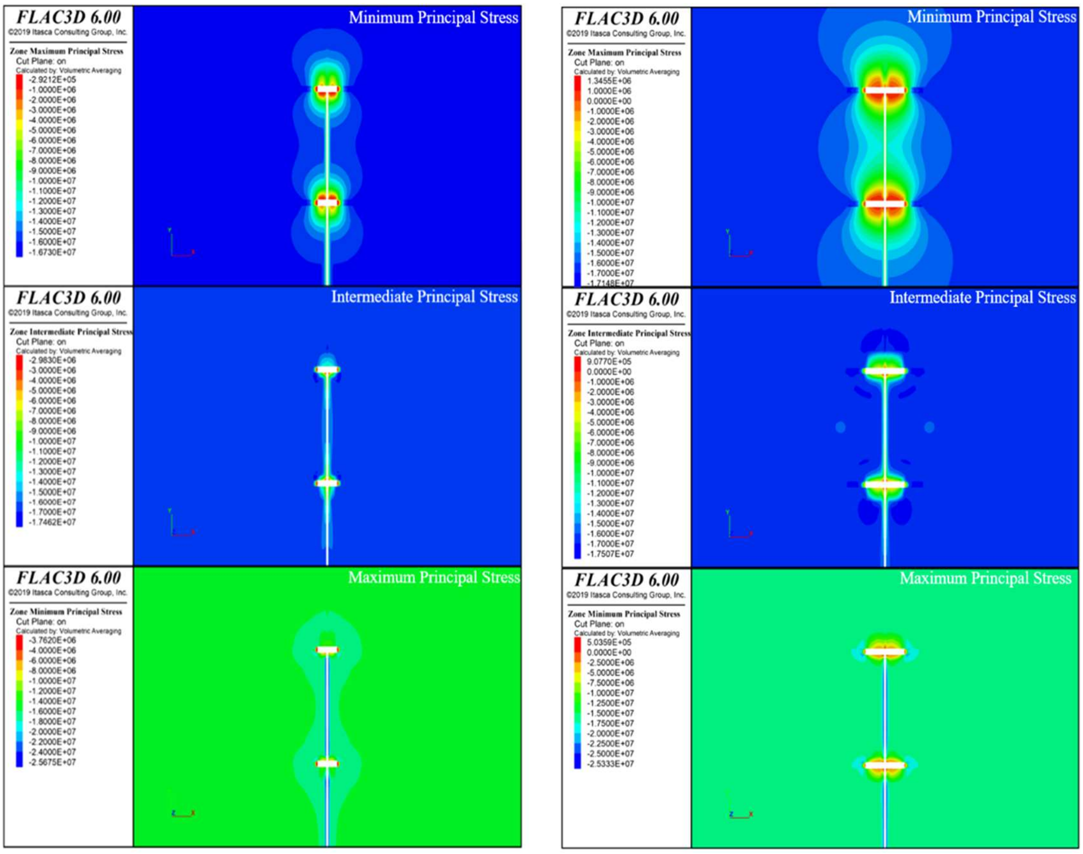


*Fig. 6. Numerical simulation analysis of ordinary borehole.*

After hydraulic flushing, the large diameter cylindrical boreholes were formed in the upper and lower tectonic soft coal seam, and the stress state of the coal seam around the borehole was secondary distributed. As shown in Fig. 7, according to the stress distribution of four groups in tectonic coal seam with different flushing radii, the maximum principal stress was the tangential stress of the hole, and the intermediate principal stress was the radial stress, and the minimum principal stress was the vertical stress. Therefore, the pressure relief effect of the stress in the vertical direction was the most obvious, and the range of pressure relief was the largest. With the release of vertical stress, the primary coal seam produced vertical swelling deformation; coal seam fracture was developed, and gas desorption and permeability were improved.

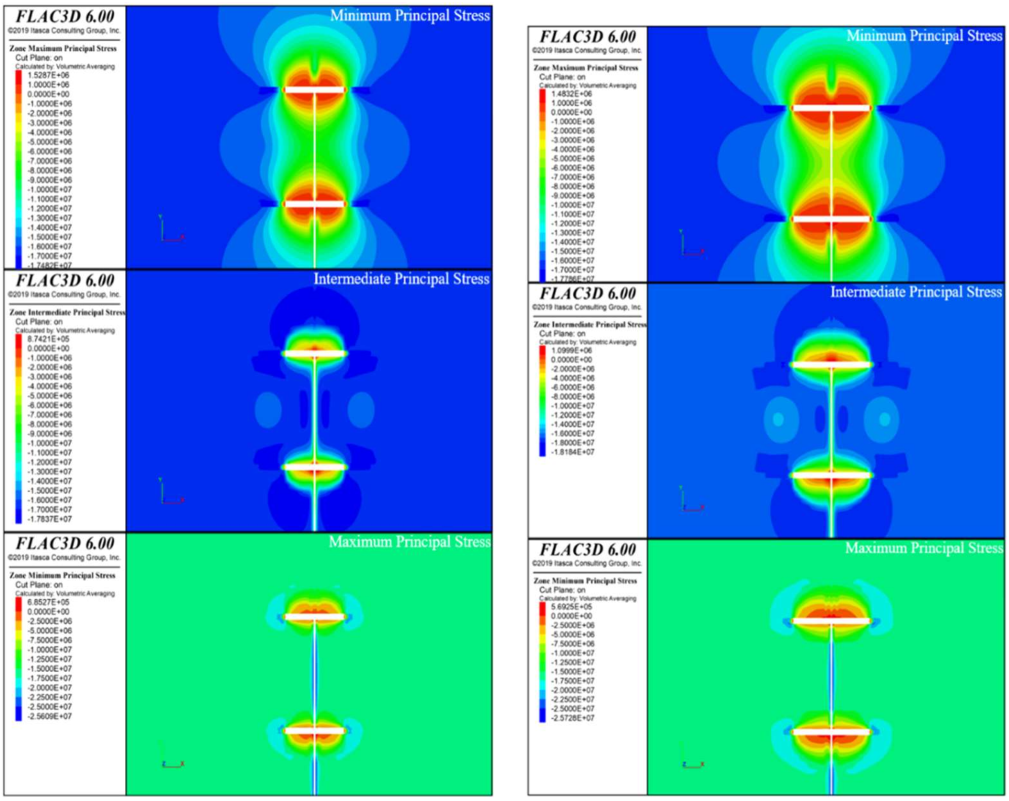
It can be seen from Fig. 7 that with the increase in punching radius, the pressure relief range of the primary coal seam was increased. When the punching diameter of the tectonic soft coal seam gradually increased from 1 m to 4 m, an inverted funnel-shaped pressure relief area was formed in the coal seam around the borehole. The pressure relief effect was greatest in the centre of the pressure relief area, which gradually decreased from the centre of the funnel to the edge. Between the upper and lower borehole of the tectonic soft coal seam, a dumbbell-shaped stress relief zone was formed in the primary coal seam. As the diameter of the coal mining increased, the pressure relief zone increased along the vertical direction of the coal seam, and the tensile stress area became more obvious. An approximately cylindrical pressure relief zone was formed within the primary coal seam around the borehole. When the punch diameter was 4 m, part of the pressure relief area changed from a compressive stress area to a tensile stress area, and the range of tension stress zone expanded with the increase of punching diameter. The stress relief zone, stress concentration zone and original stress zone were formed in front of the borehole, and the three stress zones continued to develop with the increase of punching diameter.

In general, a wide range of stress disturbances occurred in the whole coal seam area after the directional hydraulic flushing of the tectonic coal seam, especially the variation range of the minimum principal stress was the most significant. The stress in almost the entire coal seam height around the punching and drilling area had been reduced, and the primary coal near the borehole of the tectonic coal seam was the sufficient pressure relief zone. For the maximum principal stress and intermediate stress, tectonic coal and primary coal had also obtained a wide pressure relief, and the sufficient zone was the primary coal near the upper and lower borehole of the tectonic coal. But there was also some stress concentration area that appeared outside the pressure relief area around the borehole.



*(a) The punching diameter 1 m*

*(b) The punching diameter 2 m*



*(c) The punching diameter 3 m*

*(d) The punching diameter 4 m*

*Fig. 7. The coal stress nephogram around the borehole.*

As shown in Fig. 8, to study the stress distribution of the coal seam, the monitoring lines were set at *h*

= 6.88 m, $h$ = 8.57 m, and $h$ = 12.25 m ($y$-direction) in the model. The stress distribution of the coal seam was derived to analyze the pressure relief effect at different positions of the coal seam, and the stress distribution of the soft-hard composite coal seam was shown in Fig. 9. The stress distribution of upper and lower soft coal layers was basically the same, and the maximum value of the stress concentration area in front of the coal wall increased with the increase of the punching diameter. The minimum principal stress in the middle of the coal seam was the vertical stress, and its stress relief range increased with the punching diameter. There was a stress concentration area around the borehole in the hard coal seam. Since the primary coal of the Hudi mine was relatively hard, there was no plastic damage around the borehole. So the coal seam around the borehole was always in an elastic state, which led to the phenomenon of stress concentration.

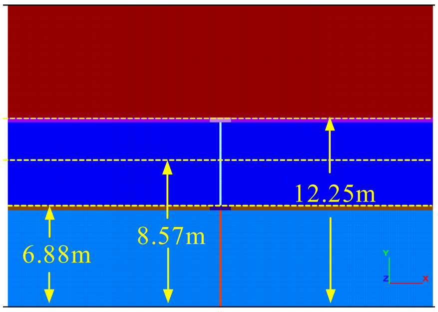
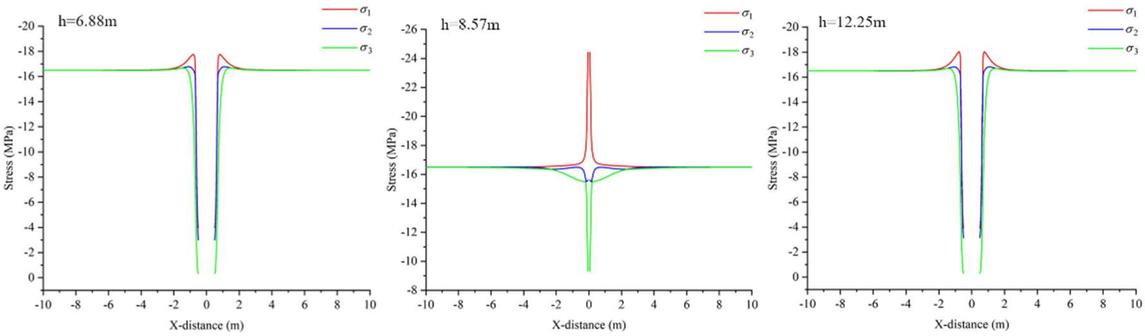
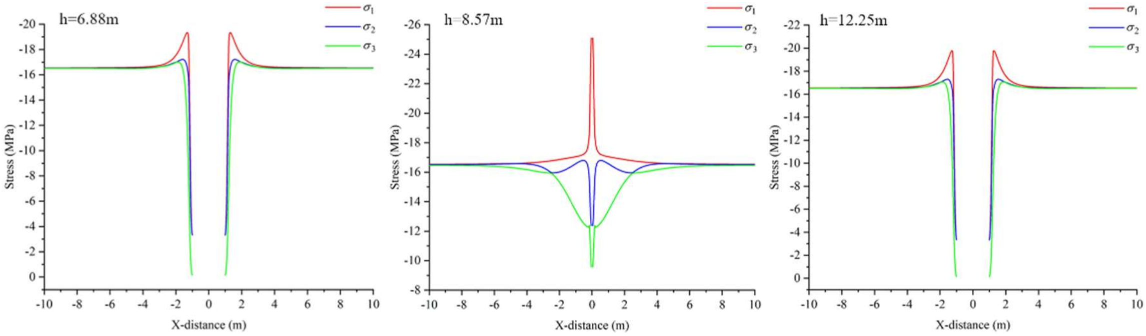


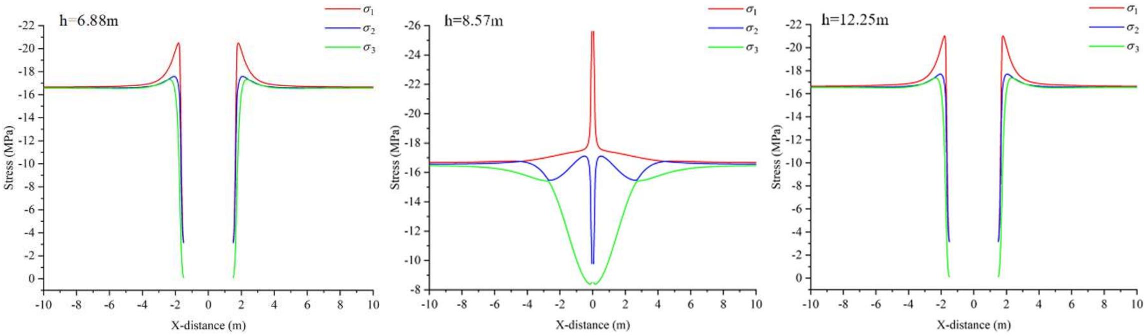
*Fig. 8. Diagram of stress monitoring lines.*



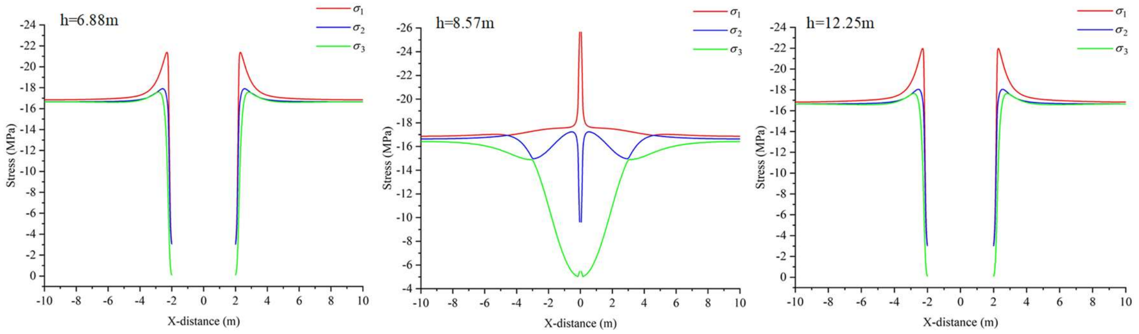
*(a) The flushing diameter 1 m*



*(b) The flushing diameter 2 m*



*(c) The flushing diameter 3 m*



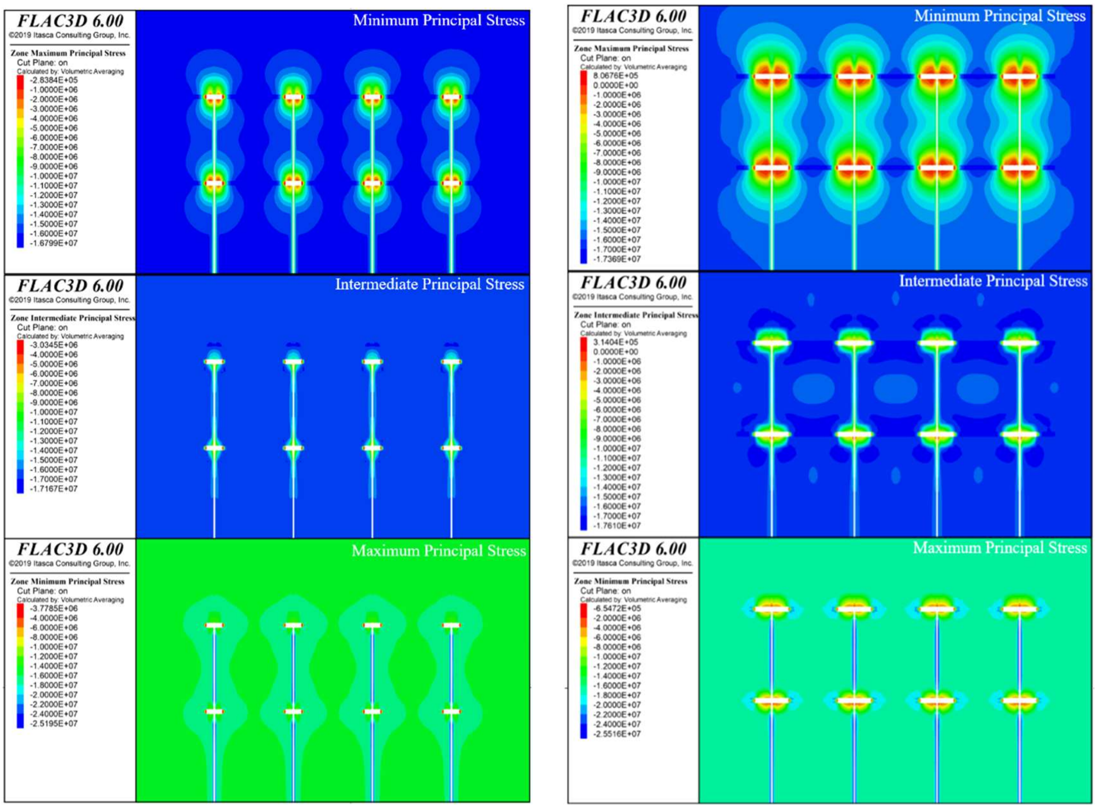
*(d) The flushing diameter 4 m*

*Fig. 9. The principal stress curves on each monitoring line.*

### Analysis of Pressure Relief Effect of Multiple Boreholes

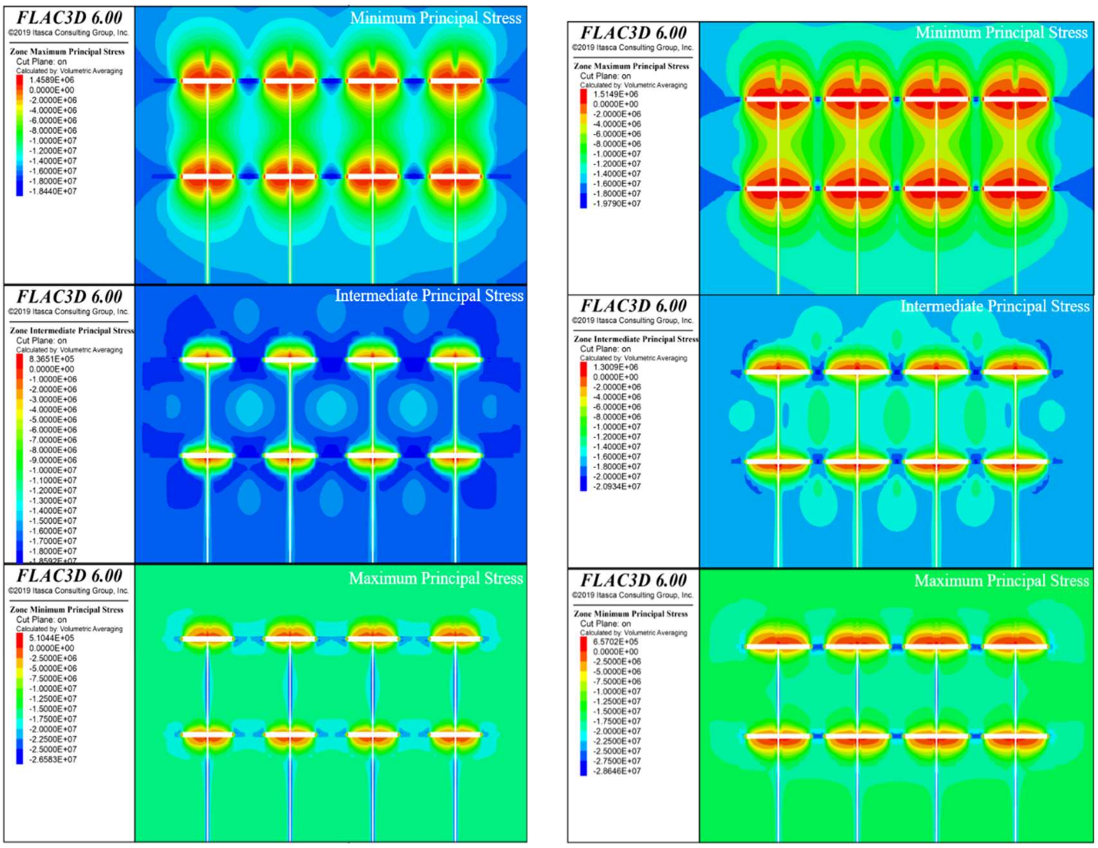
As shown in Fig. 10(a), when the punching diameter was 1 m and the hole spacing was 5 m, the pressure relief effect of each hole was consistent with the single-hole hydraulic flushing effect. However, there was a blank area between each punching borehole that was not disturbed by stress, and the coal seam did not form an overall pressure relief effect due to the small punching radius. As shown in Fig. 10(b), the overall pressure relief area was formed in the direction of the minimum principal stress between each punching borehole, and the value of minimum principal stress in the entire hard coal seam was reduced. The stress disturbance generated by each punching area covered the entire coal seam, so the coal seam got a certain degree of pressure relief effect, and the stress concentration occurred in the area outside the pressure relief area. As shown in Figs. 10(c) and 10(d), the overall pressure relief effect of the coal seam increased with the continuous increase of borehole diameter.

According to the comparative analysis of the middle principal stress nephogram, the stress concentration area around the hole relief area gradually decreased with the increase of the hole size. When the punching diameter was 4 m, the overall pressure relief effect of the principal stress direction of the coal seam was the best, and the stress concentration area existed near the residual coal pillar between the punching borehole of the tectonic coal seam. The overall pressure relief effect of the coal seam increased with the increase of the punching diameter. As the tectonic coal was flushed out, two sets of approximately layered pressure relief spaces were gradually formed in the primary coal of the roof and floor area. The stress disturbance range generated by the single hydraulic flushing borehole was connected with each other, which was similar to the pressure relief effect of the protective layer mining in the close-distance coal seam.



*(a) The flushing diameter 1 m*

*(b) The flushing diameter 2 m*



*(c) The flushing diameter 3 m*

*(d) The flushing diameter 4 m*

*Fig. 10. Numerical simulation of multiple hydraulic flushing stress nephogram.*

## Analysis of Permeability Enhancement Effect in Filed Test

Based on the numerical simulation, the predetermined hydraulic flushing plan was carried out in the tectonic coal seam area. The gas extraction concentration and flow rate were monitored after flushing, and 4 groups of hydraulic flushing boreholes and ordinary boreholes were selected at a different positions to compare the gas extraction concentration. As shown in Fig. 11, the black line represented the gas extraction concentration of the ordinary borehole, and the red line segment represented the gas extraction concentration of the tectonic soft coal seam by directional hydraulic flushing. Compared with ordinary borehole, the average gas concentration of directional hydraulic flushing had been increased from 20-30% to 50-60%. Therefore, the concentration of single hole gas drainage in soft coal seam was significantly increased after directional hydraulic flushing in the tectonic coal seam.

To study the overall pressure relief and permeability enhancement effect of hydraulic flushing in tectonic soft coal seam, the gas extraction data of 13052 coal roadways were selected for comparative analysis. As shown in Fig. 12, the black line represented the average flow of single borehole gas extraction of an ordinary borehole, and the red line represented the directional hydraulic flushing borehole. Compared with ordinary cross-seam borehole, the average daily gas extraction (ADGE) flow of hydraulic flushing borehole increased from 0.03 $m^3/d$ to 1.07 $m^3/d$. The result was obtained by the directional hydraulic flushing technology of the tectonic soft coal seam in the test, which proved that the gas extraction problem in the low permeability outburst coal seam of Hudi Coal Mine could be solved effectively by the directional hydraulic flushing.

As shown in Fig. 12, the residual tectonic coal in the 13052 roadway crept within 30 days after hydraulic flushing, which reduced the stress of the coal seam and the desorption ratios and the permeability of coal gas were improved. Therefore, the overall gas of the 13052 roadway had been effectively extracted, which greatly shortened the gas extraction cycle. After the verification of the actual 13052 roadway excavation in the later stage of the Hudi coal mine, the extraction time of the ordinary borehole area reached the area emission standard after 6 months, and the area emission standard was reached within 1 month after the directional hydraulic flushing of a tectonic coal seam being completed. The extraction cycle was shortened by 6 times, and the risk of coal and gas outburst was completely eliminated.

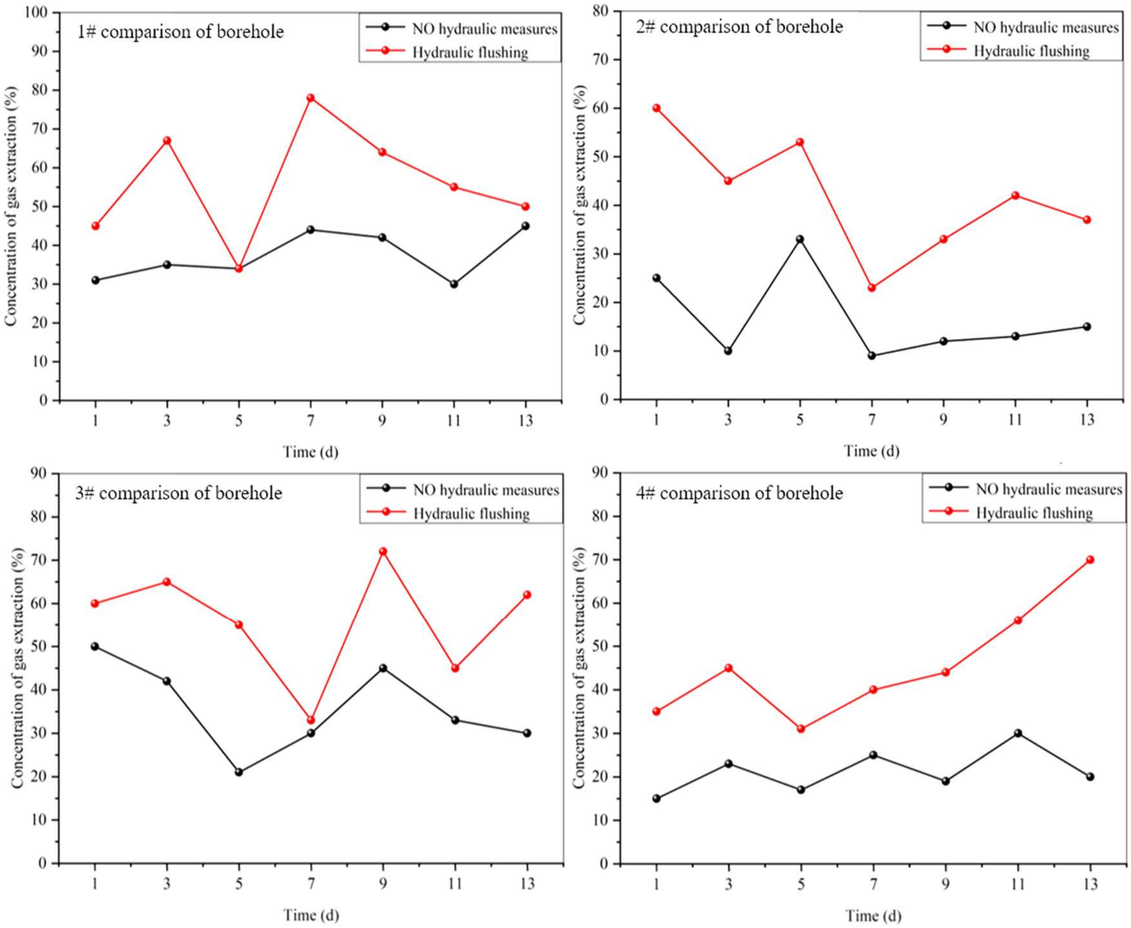


*Fig. 11. Comparison diagram of single borehole gas drainage concentration.*

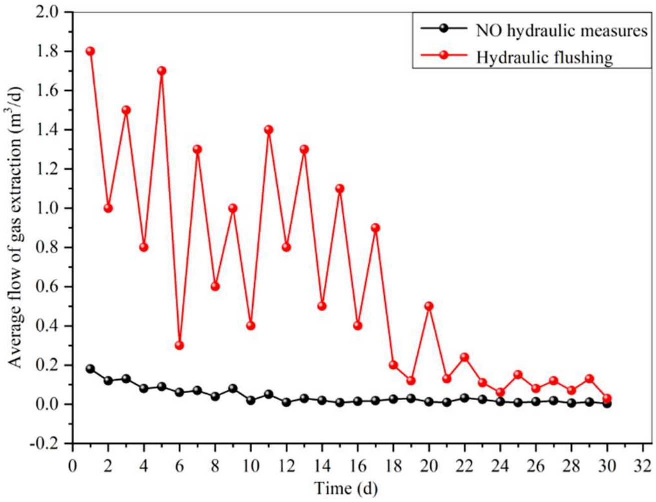
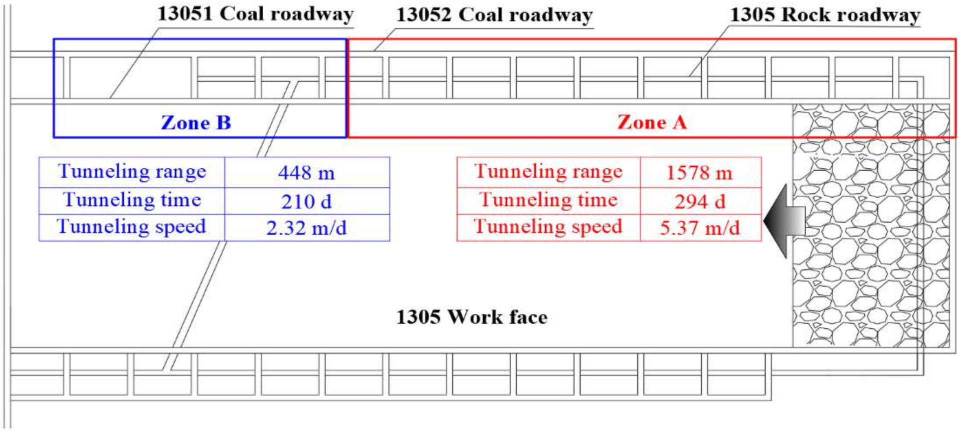
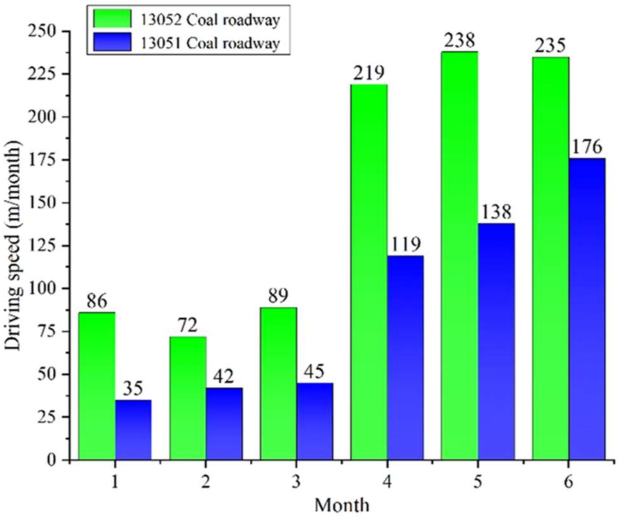


*Fig. 12. Daily average gas extraction flow curve.*

As shown in Fig. 13(a), the directional hydraulic flushing of the tectonic coal seam was carried out in zone A of 1035 working face, and zone B of 1035 working face was conducted with an ordinary cross borehole in the early stage. According to the final excavation data, the excavation speed of zone A was 5.37 m/d, and the excavation speed of zone B was 2.32 m/d. It can be seen from Fig. 13(b) that the directional hydraulic flushing of the tectonic coal seam was started in the third month, and the monthly average excavation speed in the latter three months was three times faster than in the first three months. As shown in Fig. 13, the directional hydraulic flushing technology of the tectonic coal seam enabled the gas of the entire coal seam to be fully and efficiently extracted. The roadway excavation speed was twice faster than that in the ordinary borehole area. Therefore, the excavation speed of each roadway was improved while shortening the gas drainage cycle. The dynamic balance of 'extraction, excavation, and mining' in the coal mining face with high gas content and low permeability was realized, and the efficiency of coal seam mining was significantly improved.



*(a) Daily excavation speed.*



*(b) Monthly excavation speed.*

*Fig. 13. Comparison of roadway excavation speed.*

## Conclusions

Based on theoretical analysis and numerical simulation, the gas governance problem of the soft-hard composite coal seam in the Hudi mine was taken as the research object, and the stress evolution of the composite coal seam after directional hydraulic flushing in the tectonic soft coal seam was analyzed. Combined with the field test, the following conclusions are obtained:

(1) The pressure relief range in the direction of the minimum principal stress is the most significant. With the increase of the punching diameter, the stress in almost the whole coal seam around the borehole area has decreased. The area with sufficient pressure relief is the primary coal area close to the punching area of the tectonic coal seam.

(2) As the punching diameter increases to 4 m, the influence of stress disturbance produced by single-hole hydraulic flushing is connected with each other, which is similar to the pressure relief effect of protective layer mining in the close coal seam. The stress of the whole coal seam is redistributed, and the stress in the vertical direction is reduced so that the pressure relief effect of the whole coal seam is obtained.

(3) The layered directional hydraulic flushing technology of soft coal is proposed. Directional hydraulic flushing can significantly improve gas extraction and coal roadway excavation efficiency. The average gas extraction concentration of boreholes increases from 20-30% to 50-60%, and the ADGE increases from 0.03 $m^3/d$ to 1.07 $m^3/d$.

This study revealed the stress evolution characteristics of the directional hydraulic flushing in the soft-hard composite coal seams. However, the creep deformation of the residual coal pillar in the tectonic coal seam under the stress concentration state was not considered. Further research is needed for the stress evolution of the soft-hard composite coal seam after the directional hydraulic flushing considering the creep characteristics of the soft coal pillar and the real stress state.

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