New Method for Reducing Coal Mine Gas Disasters via Directional Drilling and Hydraulic Jet

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New method for reducing coal mine gas disasters via directional drilling and hydraulic jet

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Abstract Gas extraction is an important topic because of poor permeability and high gas seam in coal mines. A new method for reducing stress and improving permeability of coal seam was proposed to reduce the cost of gas extraction and danger of coal and gas outbursts. In this method, the roadway in coal floor was replaced with directional main borehole, directional branch boreholes were used to replace crossing holes, and soft coal was mined along soft sub layers using a directional drilling machine and a directional hydraulic jet. The numerical simulation showed that the porosity and permeability of coal seam significantly improve after soft sub layers being removed by the directional hydraulic jet. The application of the proposed method and its supporting equipment was carried out under the special gas conditions of Hudi Coal Mine. Results show that the soft coal is mined efficiently along the soft sub layer using the main borehole, branch boreholes, and directional hydraulic jet. Compared the hydraulic punching in the borehole with the ordinary drilling machine, the average speed of mining soft sub layers increased from 0.5 t/h to 3.6 t/h, the equivalent diameter of mining soft sub layers increased from 1.2 m to 7.6m, and the average flow of gas extraction increased from 0.41 m^3/d to 6.25 m^3/d. The conclusions obtained in this study can provide a reference to the similar coal mining methods.

Keywords Coal mines, Directional drilling, Directional jet, Stress relief, Permeability improvement

1 Introduction

Controlling gas in coal mines has become increasingly difficult because ground stress, gas pressure, and content of coal seam continue to increase with the increase of mining depth. Coal mine gas disasters are serious accidents that affect safety of coal mining (Xia et al., 2016). Many methods have been proposed to control and prevent such disasters (Lin et al., 2015). High depth of cover, concentrated tectonic stress (Lei et al., 2019), and low permeability of some coal beds in China cause low gas extraction efficiency and high difficulty in eliminating the danger of coal and gas outbursts.

The effective reduction of stress and improvement of permeability can primarily control and prevent coal and gas outbursts in the coal seam with tectonic soft coal and thus increase the efficiency of gas drainage (Zhang et al., 2019). Protective layer exploitation can effectively reduce stress and improve permeability under the condition of multiple coal seams (Wang et al., 2008; Yang et al., 2011a; Yang et al., 2011b; Liu et al., 2011; Yang, et al., 2011c). Hydraulic measures, gas fracturing, and other measures are adopted to improve the permeability of coal seam and the efficiency of gas preextraction in single low-permeability coal seams (Lu et al., 2015; Tian et al., 2011; Lu et al., 2011; Xue et al., 2017; Lu et al., 2017). Hydraulic flushing in borehole has been widely applied to realize permeability improvement and rapid elimination of coal and gas outbursts in soft coal seams with low permeability (Hao et al., 2014; Feng et al., 2017; Li et al., 2019; Shen et al., 2015; Chen et al., 2020). However, hydraulic flushing in the borehole can likely cause stress redistribution and uniform stress distribution can be difficult to achieve. Hence, a safe and efficient alternative method of self-protective layer mining was proposed (Li et al., 2014). Directional hydraulic flushing along soft sub layers of the coal seam can be implemented using directional water jets and crossing holes. The stress of coal seam reduces and stress concentration is basically eliminated after directional hydraulic flushing and creep of residual soft coals in sub layers. However, gas extraction is a large project with long cycle and high cost.

The directional main borehole is used to replace the rock roadway in coal floor and directional branch boreholes are utilized to replace crossing holes to reduce the cost of gas extraction. At the same time, soft coal is mined along soft sub layers using the main borehole, branch boreholes, and directional hydraulic jet to relieve the stress and improve the permeability of the coal seam. By taking the special gas geological conditions of Hudi Coal Mine as an example, evolution characteristics of porosity and permeability of coal seam before and after hydraulic mining along soft sub layers were simulated with COMSOL software and the related equipment, processes, and effects of the proposed method were introduced and compared with the application in Hudi Coal Mine.
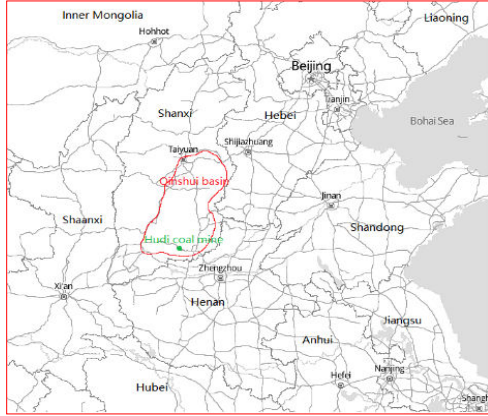
2 Research Methodology

2.1 Engineering background

The 1305 working face of No. 3 coal seam in Hudi Coal Mine was taken as the research object for numerical simulation and field test. Hudi Coal Mine is located at Qinshui Basin in Shanxi Province with geographical coordinates of east longitude 112°34'06" to 112°36'14" and north latitude 35°42'38" to 35°44'33", with a field area of 5.1253 km². The location of Hudi Coal Mine is shown in Fig. 1(a).

The designed production capacity of Hudi Coal Mine is 3 Mt/a. No. 3 coal seam was currently mined with the risk of coal and gas outbursts. The column diagram of coal seams in Hudi Coal Mine is shown in Fig. 1(b). Gas content and pressure of No. 3 coal seam is 14.48-24.56 m³/t and 1.24-3.83 MPa, respectively. Tectonic soft coal mainly occurs in the top and bottom of No. 3 coal seam in Hudi Coal Mine. The average thickness of each tectonic soft sub

layer is 0.3 m. The difficulty in extracting gas from soft sub layers causes low efficiency in gas extraction, mining, and tunneling in the coal mine. The test site located at the1305
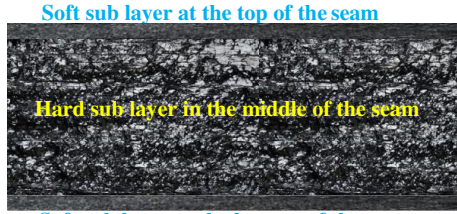
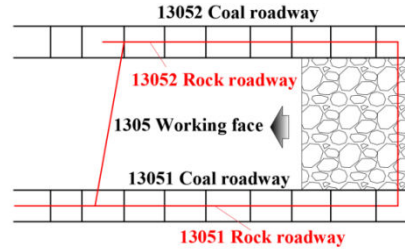working face and the roadway at the bottom of No. 3 coal seam of Hudi Coal Mine, which is illustrated in Fig. 1(d).

(a) Coal Mine location

(b) Column diagram of coal seam

(c) No. 3 coal seam structure

(d) Test site

Fig. 1 Engineering background of Hudi Coal Mine.

The gas of 1305 working face was extracted using drilling boreholes in the coal seam for 6 months prior to the test. However, the gas content of the coal seam was persistently below the standard of gas extraction and hazards of coal and gas outbursts still remain. Therefore, the new method proposed in this study was used to continue the gas extraction in the 1305 working face.

2.2 Mathematical evolution model

2.2.1 Mathematical model for porosity of coal

According to the definition of porosity:

$$\varphi = \frac{V_p}{V_b} = \frac{V_{p0} + V_p}{V_{b0} + V_b} = 1 - \frac{V_{s0} + V_s}{V_{b0} + V_b}$$
$$= 1 - \frac{1 - \varphi_0}{1 + e}\left(1 + \frac{\Delta V_s}{V_{s0}}\right)$$
(1)

where, φ is the porosity of coal, φ_0 is the initial porosity of coal, V_p is the pore volume of coal, V_{p0} is the initial pore volume of coal, V_b is the total apparent volume of coal, V_{b0} is the initial apparent total volume of coal, ΔV_p is the change in pore volume of coal, ΔV_b is the change amount of total apparent volume of coal, V_s is the skeleton volume of coal, ΔV_s is the change amount of skeleton volume of coal, e is the volumetric strain of coal.

It is assumed that the temperature of coal seam is constant, so the strain variable caused by thermoelastic expansion is 0. The interrelationship between them is as

$$\frac{\Delta V_s}{V_{s0}} = \frac{\Delta V_{st}}{V_{s0}} + \frac{\Delta V_{sf}}{V_{s0}} + \frac{\Delta V_{sp}}{V_{s0}}$$
(2)

where, $\frac{\Delta V_{st}}{V_{s0}}$ is theincrement of strain due to thermoelastic expansion, $\frac{\Delta V_{sf}}{V_{s0}}$ is theincrement of expansion strain due to the absorbed gas in coal particles, $\frac{\Delta V_{sp}}{V_{s0}}$ is the increment of compression strain due to gas pressure incoal pore.

Assuming the temperature of the coal seam is constant, so the value for $\frac{\Delta V_{st}}{V_{s0}}$ is 0, and Eq. (2) can be written as

$$\frac{\Delta V_s}{V_{s0}} = \frac{\Delta V_{sp}}{V_{s0}} - \frac{\Delta V_{sf}}{V_{s0}}$$
(3)

In Eq. (3),

$$\frac{\Delta V_{sp}}{V_{s0}} = -\frac{\Delta P}{K_s}$$
(4)

$$\frac{\Delta V_{sf}}{V_{s0}} = \frac{\xi_p}{1 - \varphi_0}$$
(5)

By combining Eqs. (3), (4) and (5), the total strain of coal particle's own deformation volume can be written as

$$\frac{\Delta V_s}{V_{s0}} = \frac{\xi_p}{1-\varphi_0} - \frac{\Delta P}{K_s} \quad (6)$$

ξ is the expansion strain of unit volume of coal after gas adsorption.

$$\xi_p = \frac{2a\rho RT}{3V_m K_s}\ln(1+bp) \quad (7)$$

where, T is the temperature of coal seam, a and b are the adsorption constant of coal, R is the universal gas constant, ρ is the density of coal, V_m is the molar volume of gas, K_s is the bulk modulus of coal skeleton.

Substituting Eqs. (6) and (7) into (1), the mathematical model of dynamic evolution of porosity can be obtained as

$$\begin{aligned}\varphi &= 1 - \frac{1-\varphi_0}{1+e}\left(1 + \frac{\xi_p}{1-\varphi_0} - \frac{\Delta P}{K_s}\right)\\ &= 1 - \frac{1-\varphi_0}{1+e}\left(1 + \frac{2aRT}{3V_m K_s(1-\varphi_0)}\ln(1+bp) - \frac{P-P_0}{K_s}\right)\end{aligned} \quad (8)$$

2.2.2 Mathematical model for permeability of coal

The mathematical relationship between porosity and permeability is established by Kozeny-Carman equation as

$$k = \frac{\varphi}{k_Z S_p^2} \quad (9)$$

In Eq. (9),

$$S_p = \frac{A_s}{V_p} \quad (10)$$

where, k is the permeability, k_Z is the dimensionless constant, S_p is the unit surface area of pore volume, A_S is the total surface area of coal pores.

The permeability in the initial state is

$$k_0 = \frac{\varphi_0}{k_z S_{p0}^2} \quad (11)$$

In Eq. (11),

$$S_{p0} = \frac{A_{s0}}{V_{P0}} \quad (12)$$

By the definition of porosity, the porosity can be obtained as

$$\varphi = \frac{V_{p0} + (\Delta V_b - \Delta V_s)}{\Delta V_{b0} - V_{b0}} \quad (13)$$

The new pore surface area is obtained as

$$S_p = \frac{A_{s0}(1+\partial)}{V_{p0} + (\Delta V_b - \Delta V_s)} \quad (14)$$

where, ∂ is the increase coefficient of coal pore surface area.

By combining Eqs. (9), (10) and (11), the ratio of the new permeability to the original permeability is obtained as

$$\frac{k}{k_0} = \frac{\varphi S_{p0}^2}{\varphi_0 S_p^2} = \frac{1}{1+e}\cdot\frac{1}{(1+\partial)^2}\cdot\left(\frac{V_{p0}+\Delta V_p}{V_{p0}}\right)^3 \quad (15)$$

During the stress and strain of coal, the total surface area of coal particle per unit volume can be regarded as unchanged and ignored, so $\partial \approx 0$. Then Eq. (15) can be simplified as

$$\frac{k}{k_0} = \frac{1}{1+e}\left(\frac{V_{p0}+\Delta V_p}{V_{p0}}\right)^3 \quad (16)$$

In Eq. (16),

$$\frac{V_{p0}+\Delta V_p}{V_{p0}} = 1 + \frac{e}{\varphi_0} - \frac{\Delta V_s}{V_{s0}}\cdot\frac{(1-\varphi_0)}{\varphi_0} \quad (17)$$

By combining Eqs. (6), (7), (15), (16) and (17), the mathematical model for permeability of coal containing gas is obtained as

$$k = \frac{k_0}{1+e}\left[1 + \frac{e}{\varphi_0} + \frac{\Delta P(1-\varphi_0)}{\varphi_0 k_s} - \frac{2a\rho RT\ln(1+bp)}{3\varphi_0 V_m K_s}\right]^3 \quad (18)$$

2.3 Numerical modeling analysis

2.3.1 Geometric model

COMSOL software was used to simulate the porosity and permeability after directional mining of soft sub layers. The geometric model of the simulation was built according to geological conditions of the 1305 working face in Hudi Coal Mine. The average thickness of No. 3 coal seam is approximately 5.7 m at the 1305 working face. Stable soft sub layers with a thickness of 0.3 m can be found at the top and bottom of No.3 coal seam. The roof and floor of the coal seam are composed of mudstone and sandstone. The length, width, and height of the calculation model in the simulation were set to 25, 25, and 49.6 m, respectively, to avoid the influence of boundary effect. The height of the roof and floor is 22 m. The length of the crossing hole in the model is 24.6 m, and the mining diameter in soft sub layers is set to 2, 2.5, 3, 3.5, and 4 m. The geometric model of the numerical simulation is illustrated in Fig. 2(a).

The "special coarse" unit size of the model roof and floor in the software and the "refined" unit size of the coal seam in the software were used for subdivision. The model subdivision network is shown in Fig. 2(b). The experimental procedure was transient, the study step length was 1 day, and the numerical simulation ran for 180 days.
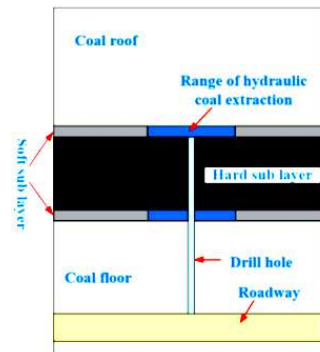
(a) Geometric model of numerical simulation
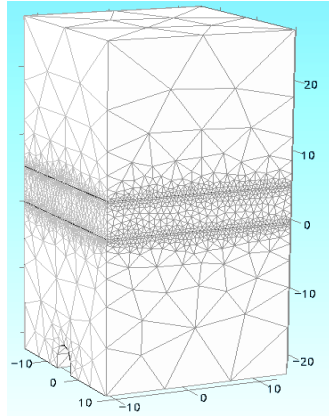
(b) Mesh generation of geometric model

Fig. 2 The computational model.

2.3.2 Parameters of numerical simulation

These parameters of the numerical simulation include density, Poisson's ratio, initial porosity, and initial permeability of coal as well as adsorption constants, gas dynamic viscosity coefficient, coal moisture, and coal ash. Specific physical parameters are listed in Table 1.
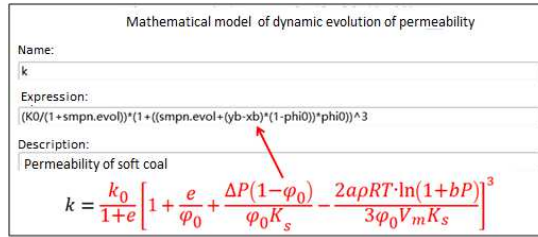
2.4 Numerical results analysis

In order to simulate evolution characteristics of porosity and permeability in coal seams before and after directional hydraulic mining along to soft sub-layers, the mathematical model of coal porosity and coal permeability are input into the corresponding setting module of COMSOL multi-physics simulation. The corresponding setting module are shown in Fig. 3.

Table 1 Physical parameters of gas-bearing coal.

Name	Symbol	Value	Unit
Density of soft coal	ρ	1320	$kg \cdot m^{-3}$
Density of hard coal	ρ_y	1851	$kg \cdot m^{-3}$
Poisson's ratio of soft coal	v	0.39	/
Poisson's ratio of hard coal	v_1	0.32	/
Modulus of elasticity of soft coal	E	0.978	GPa
Modulus of elasticity of hard coal	E_1	3.2	GPa
Initial porosity of soft coal	φ_0	0.049	/
Initial porosity of hard coal	φ_{0y}	0.095	/
Initial permeability of soft coal	k_0	4.59×10^{-18}	m^2
Initial permeability of hard coal	k_{0y}	1.3×10^{-15}	m^2
Adsorption constant	a	30.71	$m^3 \cdot t^{-1}$
Adsorption constant	b	1.8	MPa^{-1}
Gas dynamic viscosity coefficient	μ	1.08×10^{-5}	$Pa \cdot s$
Soft coal moisture	M	0.1285	/
Hard coal moisture	M_1	0.0487	/
Soft coal ash	A	0.1532	/
Hard coal ash	A_1	0.1339	/
Standard gas density	ρ_g	0.716	$kg \cdot m^{-3}$
Initial gas pressure	P_0	2.36	MPa
Negative pressure	P_1	-25 000	Pa
Universal gas constant	R	8.314	$J/mol \cdot K^{-1}$
Molar mass of methane gas	M_g	16.04×10^{-3}	kg/mol
Molar volume of gas	V_m	22.4	L/mol
Vertical stress	σ_z	16.47	MPa
X axis horizontal stress	σ_x	9.41	MPa
Y axis horizontal stress	σ_y	18.34	MPa

$$k = \frac{k_0}{1+e}\left[1 + \frac{e}{\varphi_0} + \frac{\Delta P(1-\varphi_0)}{\varphi_0 K_s} - \frac{2a\rho RT \cdot \ln(1+bP)}{3\varphi_0 V_m K_s}\right]^3$$

(a) Corresponding setting module for permeability of coal containing gas

$$\varphi = 1 - \frac{1-\varphi_0}{1+e}\left(1 + \frac{2a\rho RT}{3V_m K_s(1-\varphi_0)}\ln(1+bP) - \frac{P-P_0}{K_s}\right)$$
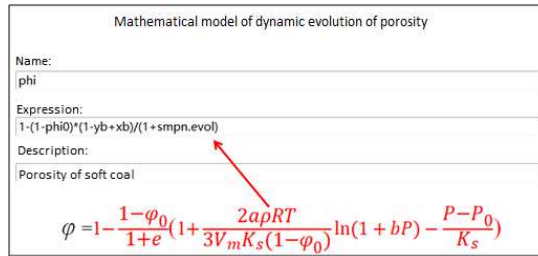
(b) Corresponding setting module for permeability of coal containing gas

Fig. 3 Corresponding setting module.

The results of simulation are presented in Fig. 4. The gas extraction time is 180 days, the borehole diameter is 0.095 m, and the diameter of hydraulic mining in the soft sub layer at the bottom a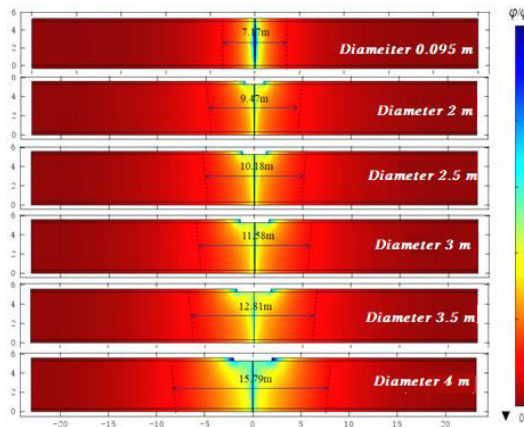nd top of the coal seam is 2.0, 2.5, 3.0, 3.5, and 4.0 m. The porosity and permeability of coal seams improve significantly after hydraulic mining in the soft sub layer and increase with the increase of the diameter of hydraulic mining in the soft sub layer.
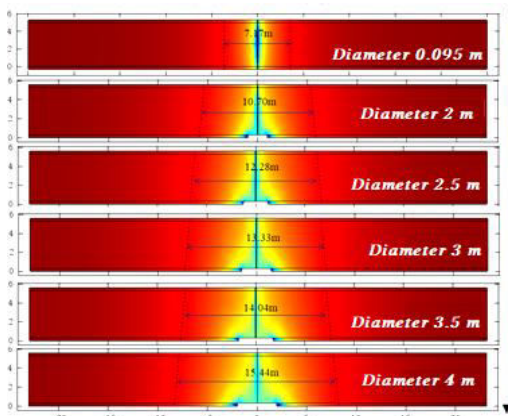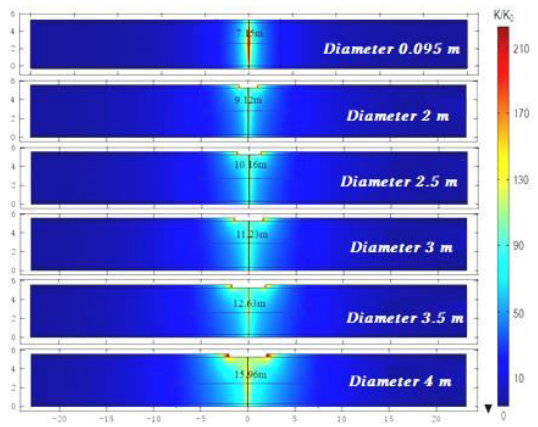

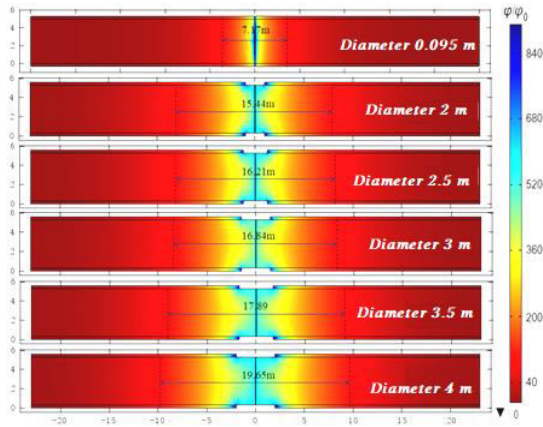(a) Porosity of coal after mining at the bottom
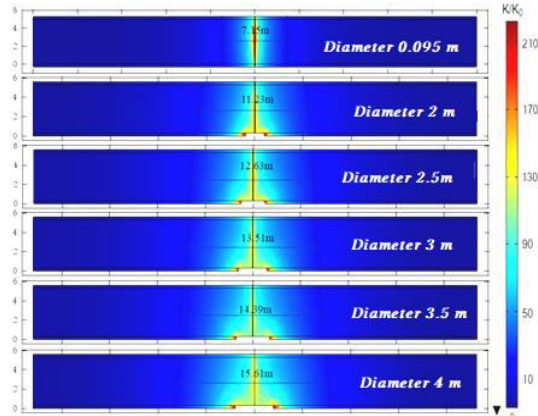
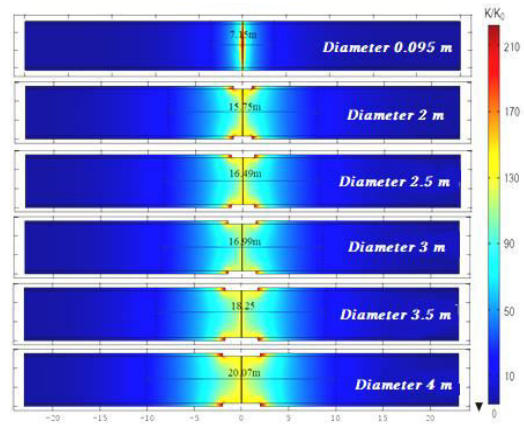(b) Permeability of coal after mining at the bottom

(c) Porosity of coal after mining at the top

(d) Permeability of coal after mining at the top

(e) Porosity of coal after mining at the bottom and top

(f) Permeability of coal after mining at the bottom and top

Fig. 4 Porosity and permeability of coal seams.

The simulation was conducted to analyze the improvement of the porosity and permeability after hydraulic mining in the soft sub layer. The average influence range of porosity and permeability of the crossing hole without hydraulic mining in the soft sub layer are 7.17 and 7.15 m, respectively. The average influence range of porosity and permeability of hydraulic mining in the soft sub layer at the bottom of the coal seam are 15.44 and 15.61 m, at the top bottom of coal seam are 15.79 and 15.96 m, and at the top and bottom of the coal seam are respectively 19.65 and 20.07 m, respectively, when the diameter of hydraulic mining in the soft sub layer is 4 m. The influence range of porosity and permeability are larger after hydraulic mining at the bottom and top soft sub layers.

3 Field tests

3.1 Test Principle

The directional drilling machine and hydraulic jet are used to mine soft sub layers, achieve the effect of mining self-protective layers, and realize rapid stress relief and permeability improvement of the coal seam with soft sub layers. The surrounding rock stress reduces and gas desorption and permeability of the residual layer of coal seam improve rapidly after directional hydraulic mining along soft sub layers to realize the efficient regional gas extraction and risk elimination of coal and gas outbursts. Theory on permeability improvement with the directional drilling machine and hydraulic jet is shown in Fig. 5. This method has the advantages of satisfactory reliability, high efficiency, and low cost. A uniform area of pressure relief can be formed within the entire mining range of the coal seam in a short time after directional hydraulic mining and the creep of the residual soft coal in soft sub layers to solve the stress concentration phenomenon caused by hydraulic measures, such as hydraulic punching and fracturing.
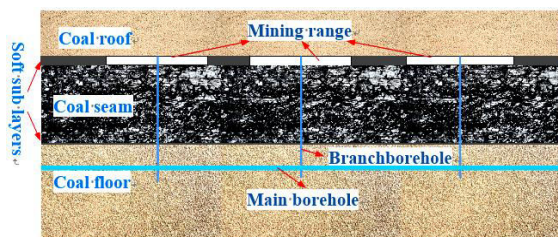
Fig. 5 Profile for permeability improvement by directional drilling machine and hydraulic jet.

3.2 Method processes

Main boreholes are constructed parallel to the seam in the coal seam floor, and branch boreholes are opened in the floor and coal seam. The branch borehole consists of two parts, namely, the crossing hole and the soft sub layer parallel to the seam. Both main and branch boreholes are constructed using a high-power directional drilling machine. The directional hydraulic jet is used for hydraulic mining during the process of retracting drill pipes in the second part of branch boreholes. Fig. 6 shows the layout of directional hydraulic mining with the high-power directional drilling machine along the soft sub layer.
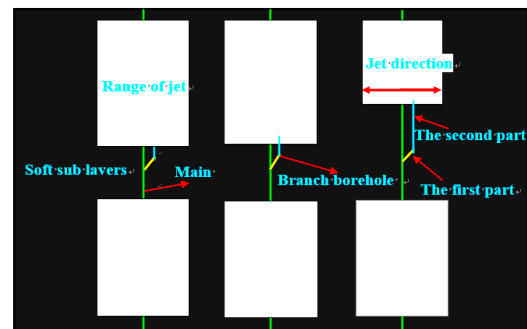
Fig. 6 Directional hydraulic mining by high-power directional drilling machine.

3.3 Test equipment

As shown in Fig. 7, the equipment used in the test of mining soft sub layers in Hudi Coal Mine mainly includes the ordinary drilling machine, directional drilling machine, high-pressure water pump, high-pressure sealing rotary device, high-pressure pipes, high-pressure valves, high-pressure sealing drill pipes, directional jet device along soft sub layers, and gas-water separation device.

(a)

(b)
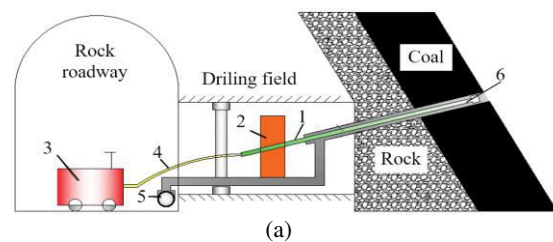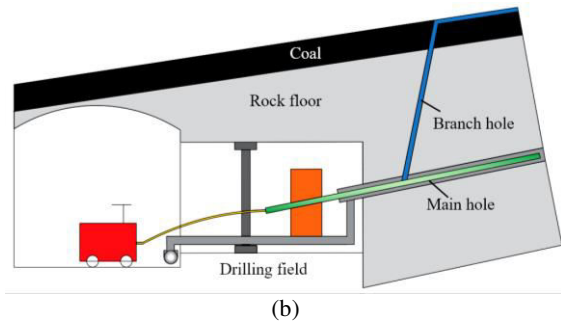
1-drill pipe, 2-drilling machine, 3-high-pressure water pump, 4-high-pressure pipe, 5-the device of gas water separation, 6-the device for directional jet along soft sub layers.

Fig. 7 Equipment used in the test.

The device for directional jet with the ordinary drilling machine is mainly composed of plug-type sealed steel tubes, reducer union, universal joint, and hydraulic spin sprinkler with jet torque, as shown in Fig. 8(a). The angle between universal joint and nozzle is adjusted according to the angle between the crossing borehole and the coal seam before mining soft sub layers to ensure that the jet direction of the nozzle is nearly parallel to the coal seam. The ordinary drilling machine is used to send the device for directional jet into the soft sub layer of the coal seam, and the direction of the hydraulic spin sprinkler with jet torque is adjusted according to the azimuth calibrated in plug-type sealed steel tubes to ensure that the direction of the rotating jet is nearly parallel to the coal seam, as shown in Fig. 8(a).
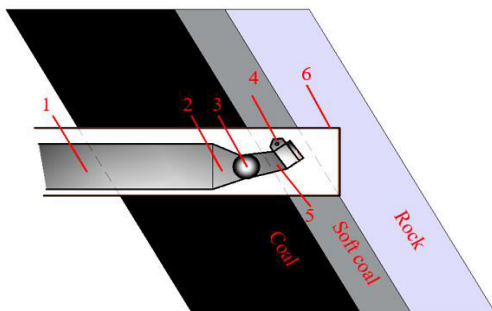
1-plug-type sealed steel tubes, 2-reducer union, 3-universal joint, 4-nozzle, 5-hydraulic spin sprinkler with jet torque, 6-the crossing hole.

(a) Device for directional jet with ordinary drilling machine
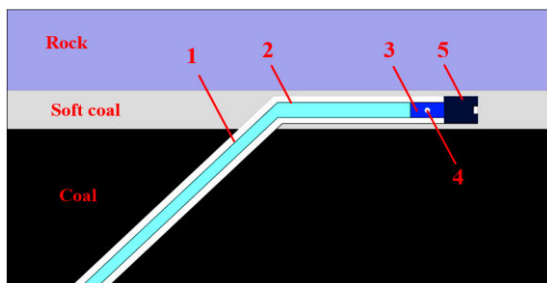
1-branch borehole, 2-directional drilling pipe, 3-transfer joint for high and low water pressure, 4-directional nozzle, 5-directional drill

(b) Device for directional jet with directional drilling machine

Fig. 8 Device for directional jet.

Two directional nozzles are fixed on both sides of the transfer joint for high and low water pressure and the transfer joint for high and low water pressure are connected between the directional drill and directional drilling pipe, as shown in Fig. 8(b). The pressure of water in the directional drilling pipe is increased, the water channel at the front of the transfer joint is closed, directional nozzles are opened, and the soft coal is mined by jets, which are produced by directional nozzles and parallel to the soft sub layer of the coal seam, when the branch borehole in the soft sub layer is completed.

ZDY4200LPS(A) is the ordinary drilling machine used for directional hydraulic mining along the soft sub layer of the coal seam. The high-power directional drilling machine ZYL15000D is also used in the 1.5 km-long borehole to improve the efficiency of directional hydraulic mining along the soft sub layer of the coal seam. High-pressure water pumps BRW 200/31.5 and BRW 400/31.5used in the test were fitted with caterpillars to allow self-mobility. The rated flow of pumps is 200 and 400 L/min and their rated pressure is 31.5 MPa.

3.4 Technological parameters

Gas extraction data from conventional hydraulic flushing in boreholes, directional hydraulic mining with a common drilling machine and directional hydraulic mining with a directional drilling machine were compared and analyzed. Two soft sub layers were adopted as self-protective seam mining in the directional hydraulic mining of No. 3 coal seam in Hudi Coal Mine. The thickness of each soft sub layer is 0.5 m, and the hardness coefficient of the soft sub layer is 0.1-0.2. The spacing of boreholes is set to 5-10 m for the comparison of gas extraction data. The pressure and flow of jet are set to 10-28 MPa and 70-280 L/min, respectively.

3.5 Test results

The test site was divided into zones A, B, and C, as shown in Fig. 9. Directional hydraulic mining with the common drilling machine was tested in zone A, and the spacing of boreholes was set to 7 m. Conventional hydraulic flushing in boreholes was tested in zone B, and the spacing of boreholes was set to 5 m. Directional hydraulic mining with the directional drilling machine was tested in zone C, and the spacing of boreholes was set to 5-10 m.
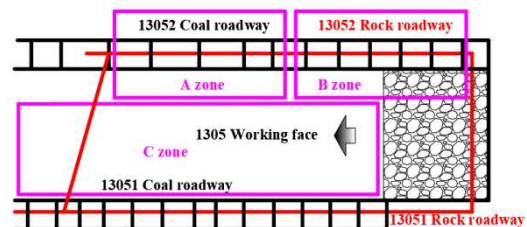

Fig. 9 Test zone.

3.5.1 Tests with the common drilling machine

Tests with the common drilling machine in zones A and B of the 1305 working face and rock roadway began on August 1, 2018. The jet pressure and flow rate of the test were set to10-28 MPa and 70-180 L/min, respectively. As

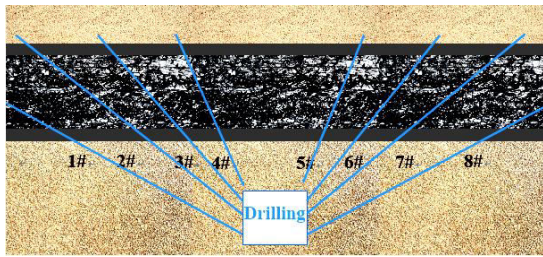shown in Fig. 10, boreholes are symmetrically arranged in the 1305 working face and rock roadway.

Fig. 10 Arrangement of crossing boreholes.

Directional hydraulic mining in zone A is only carried out in soft sub layers, and the direction of water jet is parallel to soft sub layers. The range of directional hydraulic mining is presented in Fig. 11(a). The upper soft layer was mined in #1, #3, #6, and #8 boreholes, and both soft layers were mined in #2, #4, #5, and #7 boreholes. Zone A has 100 groups of crossing boreholes, parallel spacing between groups is 7 m, and the average distance between crossing boreholes in the coal seam is 7 m. The device for the directional jet was sent to soft sub layers, and directional mining along the soft sub layer was carried out after retracting drill pipes.

The residual soft coal in soft sub layers appeared to creep under the action of concentrated stress, the thickness of the residual soft coal reduced, the hard sub layer of the coal seam expanded and thickened, the stress reduced, and cracks increased after directional hydraulic mining in Zone A. The effect of pressure relief and permeability improvement is shown in Fig. 11(b).
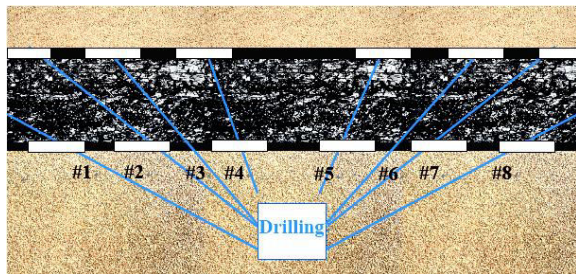
(a) Range of directional hydraulic mining
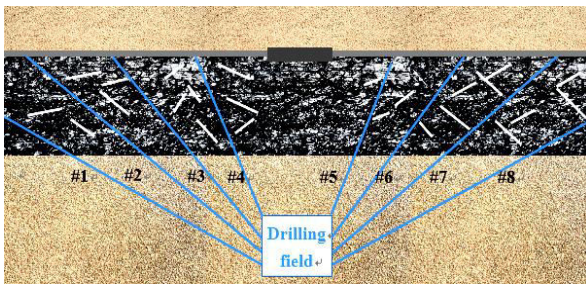
(b) Effect of pressure relief and permeability improvement

Fig. 11 Test in zone A.

Common hydraulic flushing was carried out in every other drill borehole in the coal seam of zone B. The scope of common hydraulic flushing in boreholes with the common drilling machine in zone B is shown in Fig. 12. The water jet perpendicular to the crossing hole was used for hydraulic flushing in #2, #4, #5, and #7

boreholes. Zone B has 100 groups of crossing boreholes, the parallel spacing between groups is 5 m, and the average distance between crossing boreholes in the coal seam is 5 m. Common hydraulic flushing was carried out in boreholes while retracting drill pipes.
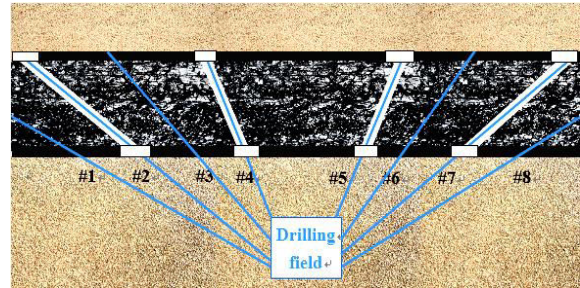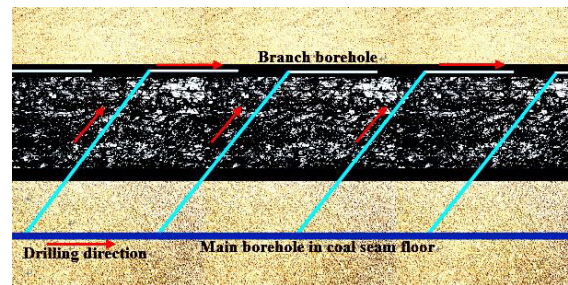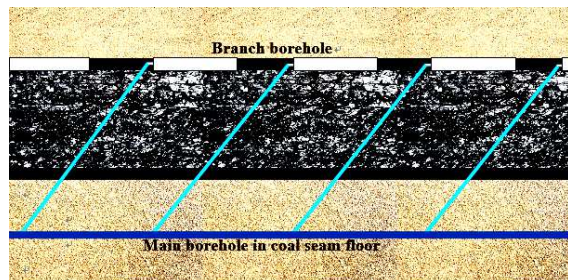

Fig. 12 Test in zone B.

3.5.2 Tests with the directional drilling machine

Tests with the directional drilling machine in zone C of the 1305 working face began on May 12, 2019. The jet pressure and flow rate of the test were set to10-28 MPa and 120-380 L/min, respectively. Main boreholes were constructed in the rock under the coal seam, and crossing holes were manufactured as branch boreholes using the high-power directional drilling machine. Main boreholes are spaced 10 m apart, and the branch borehole is 5-10 m in length along the soft sub layer. The arrangement of boreholes in directional hydraulic mining in zone C is illustrated in Fig. 13(a). Directional mining was carried out in branch boreholes along the soft sub layer while retracting drill pipes. The residual soft coal in soft sub layers is shown in Fig. 13(b). The residual soft coal creped and thinned, the pressure of the hard sub layer was relieved, and permeability increased after directional mining in the soft sub layer, as shown in Fig. 13(c).

(a) Boreholes of directional hydraulic mining

(b) Scope of directional hydraulic mining
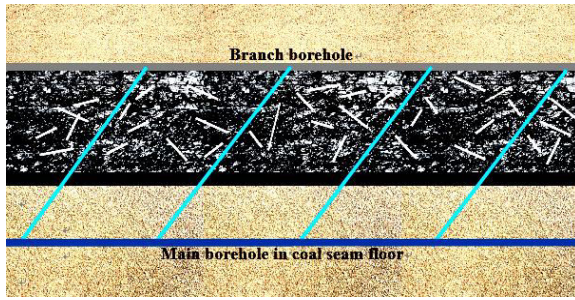
(c) Effect of pressure relief and permeability improvement

Fig. 13 Test in zone C.

3.5.3 Test data

Test data for 3 months in zones A, B, and C are listed in Table 2. The comparison showed that the efficiency of hydraulic punching in the borehole with the ordinary drilling machine is very low and that of directional hydraulic mining along soft layers is high, especially in the directional hydraulic mining of the coal seam with soft sub layers using the directional drilling machine. The average speed of mining soft sub layers reached 3.6 t/hour, which is 7.2 times that of conventional hydraulic punching in the borehole with the ordinary drilling machine.
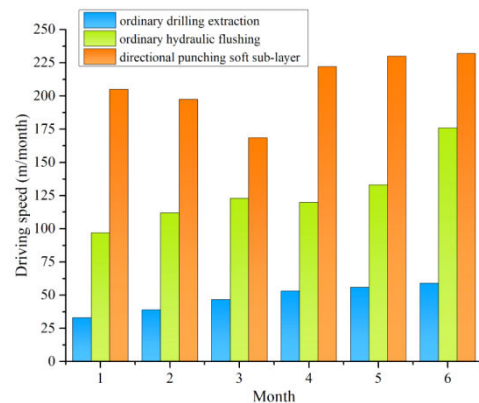
Table 2 Test data.

Type of test	Average speed of hydraulic mining (t/hour)	Diameter of hydraulic mining (m)	Average concentration of gas extraction (%)	Average flow of gas extraction (m³/d)
Hydraulic punching in borehole by ordinary drilling machine	0.5	1.2	28.4	0.18
Directional hydraulic mining by ordinary drilling machine	1.8	5.6	36.5	0.63
Directional hydraulic mining by directional drilling machine	3.6	7.6	56.7	1.07

The concentration and flow of gas extraction of directional hydraulic mining with the directional drilling machine are higher, the average concentration is 56.7%, and the average flow is 6.25 m^3/d. By comparison, the concentration and flow of gas extraction of conventional hydraulic punching in the borehole with the ordinary drilling machine are lower, the average concentration is 28.4%, and the average flow is 0.41 m^3/d.

The driving speed of the 13052 coal roadway is used for comparative analysis to investigate the effect of directional hydraulic mining of the soft sub layer, as shown in Fig. 14. The long square blue column represents the driving speed after conventional extraction for 180 days without any hydraulic measures. The long square green column represents the driving speed after conventional extraction for 90 days with conventional hydraulic punching in the borehole using the ordinary drilling machine. The long square tawny column represents the driving speed after the special extraction for 30 days with directional hydraulic mining in the borehole with the ordinary drilling machine. Fig. 14 presents that directional hydraulic mining improves the driving speed of the coal roadway. The residual soft coal crept and the stress of the coal seam reduced evenly in the working face of the 13052 coal roadway after 30 days of directional hydraulic mining in the soft sub layer, thereby causing even gas desorption and permeability improvement. Hence, the uniform and efficient extraction of gas in the 13052 coal roadway significantly reduced the time of gas extraction and improved the driving speed.

Fig. 14 Driving speed of coal 13052 roadway.

Residual gas extraction increased in difficulty because the gas of the 1305 working face was extracted using drilling holes in the coal seam before the test. Gas extraction of the 13052 coal roadway was used for comparative analysis to investigate the effect of directional hydraulic mining of the soft sub layer, as shown in Fig. 15. The black square, red ball, and blue triangle represent the average flow of gas extraction for a single borehole without any hydraulic measures, with conventional hydraulic flushing in the borehole, and with directional hydraulic mining in soft sub layers, respectively. Fig. 15 shows that directional hydraulic mining significantly improves the average flow of gas extraction. Compared with that of hydraulic punching in the borehole, the average flow of gas extraction increased from 0.41 m^3/d to 6.25 m^3/d with directional hydraulic mining in soft sub layers. According to the verification of the actual coal roadway driving process in Hudi Coal Mine, the regional drainage standard is achieved in 30 days after the completion of directional

hydraulic mining. Hence, the risk of coal and gas outbursts is completely eliminated and safety requirements of coal roadway driving are met.
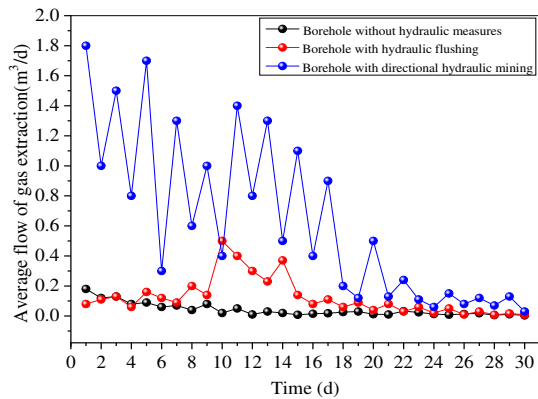

Fig. 15 Comparative analysis of gas extraction data.

4 Discussion

Data from tests of zones A and C were used to analyze the influence of creep time, water jet parameters, and width of residual soft coal on pressure relief and gas drainage of the coal seam.

4.1 Influence of creep time on pressure relief

The permeability of the coal seam before and after directional hydraulic mining was measured in test area A to discuss the influence of directional hydraulic mining in soft layers on pressure relief and permeability improvement of the coal seam. The average initial permeability of the coal seam in the experimental area is 25 $m^2/(MPa^2 \cdot d)$, which increased to 408 $m^2/(MPa^2 \cdot d)$ after 30 days of directional hydraulic mining. Analysis of the coal seam exposed by the working face demonstrated that boreholes are absent in soft sub layers, the thickness of soft sub layers significantly reduce during tunneling in zones A and C, a portion of boreholes in soft sub layers is filled during tunneling in zone B, and the change in thickness of soft sub layers is non-significant after 90 days of directional hydraulic mining in the 1305 working face. Figs. 11 and 13 show the soft coal creep deformation and stress relief after directional hydraulic mining in zones A and C. The residual pillar is relatively wide and the creep deformation and stress relief are unclear after conventional hydraulic punching in the borehole with the ordinary drilling machine in zone B.

The average thickness of the residual soft coal with different creep times was measured after directional hydraulic mining during the process of working face mining in Zone C to verify the influence of time on the creep of soft coal and the stress relief of the coal seam. The equivalent width of the residual soft coal is 2.4m, the average initial thickness is 0.52 m, and the final average thickness is 0.22 m after 90 days of directional hydraulic mining, as shown in Fig. 16. The average thickness of the residual soft coal significantly reduced after 20 days of directional hydraulic mining of soft coal; hence, the stress of the coal seam will reduce rapidly in 20 days. The creep of the residual soft coal

between boreholes in the soft sub layer increased, the soft coal thinned, and the permeability of the coal seam further increased with the increase of time.
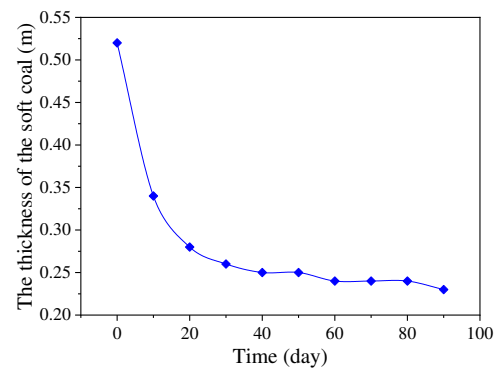

Fig. 16 Thickness of residual soft coal with different creep time.

4.2 Influence of the jet on the efficiency of directional hydraulic mining

Different output pressures in the range of 10-28 MPa and the high-pressure water pump BRW 400/31.5 were used for the test in Zone C to analyze the influence of jet pressure and flow rate on the efficiency of directional hydraulic mining. This high-pressure pump is quantitative, and the effective flow rate of output decreases with the increase of stress. As shown in Fig. 17, the efficiency of directional hydraulic mining first increases with the increase of jet pressure and decrease of flow rate and then reaches the optimal efficiency at 20 MPa. The jet flow is insufficient, the effective range of the jet begins to decrease, and the efficiency of directional hydraulic mining decreases as the pressure continues to increase.

4.3 Influence of the residual soft coal width on stress relief

As different jet pressure and boreholes spacing would form the residual soft coal with different width. The spacing of drilling holes is 10 m, the jet pressure is 10-28 MPa, the equivalent diameter of the residual soft coal is 1.5-7.6 m, and the equivalent width of the residual soft coal is 2.4-8.5 m for directional hydraulic mining in zone C. The residual soft coal with different equivalent widths is used to verify its influence on the stress relief of the coal seam, as shown in Fig. 18. The large width of the residual soft coal increases its average thickness under the condition of the same time. Therefore, the width of the residual soft coal should be appropriately reduced to improve the relief effect of the coal seam.
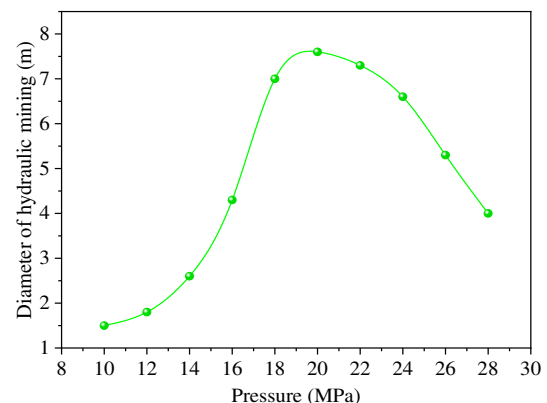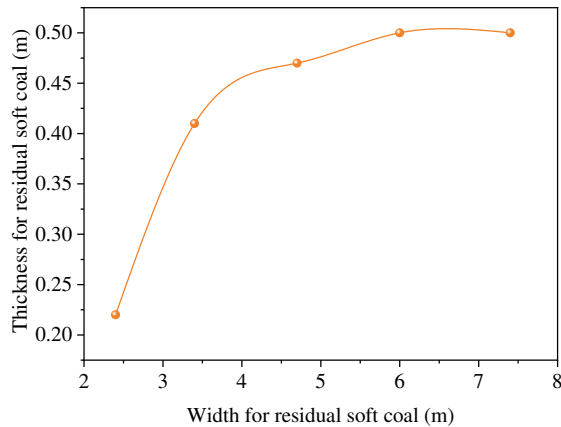
(a) Influence of jet pressure rate on efficiency of directional hydraulic mining
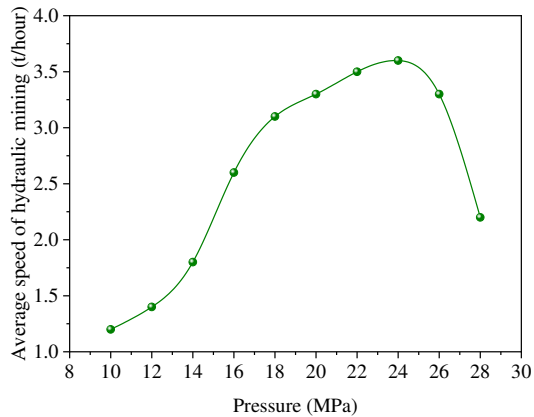
(b) Influence of flow rate on efficiency of directional hydraulic mining

Fig. 17 Influence of jet on efficiency of directional hydraulic mining.

Fig. 18 Influence of residual soft coal width on thickness of residual soft coal.

5 Conclusions

Gas extraction is difficult with serious threat of disaster underground for a single coal seam with poor permeability and high danger of coal and gas outbursts. Extracting gas via rock roadway and crossing holes in the coal floor is a conventional method to solve this problem. An alternative method for reducing stress and improving gas extraction is proposed in this study to reduce the cost and improve the efficiency of gas extraction. We carried out numerical simulation and applied the proposed method using the special gas geological conditions of Hudi Coal Mine as an example. The following conclusions can be drawn from this study:

The soft coal in soft sub layers can be removed effectively with the directional drilling machine, the directional hydraulic jet, main boreholes, and branch boreholes via the proposed method. The stress is relieved and the permeability increases in the coal seam after extraction of the soft coal from soft sub layers. The directional main borehole can be used to replace the rock roadway in the coal floor and directional branch boreholes

can be utilized to replace crossing holes to reduce the cost of gas extraction.

The simulation results based on COMSOL Multiphysics showed that the porosity and permeability of coal seams significantly improve after hydraulic mining in soft sub layers and the porosity and permeability increase with the increase of diameter of hydraulic mining in soft sub layers. The average influence range of porosity and permeability for hydraulic mining in soft sub layers at the top and bottom of the coal seam are 19.65 and 20.07 m, respectively, when the diameter of mining soft sub layers at the top and bottom of the coal seam reaches 4 m.

The proposed method and related equipment were applied in Hudi Coal Mine. The application results showed that the soft coal is mined efficiently and the permeability of coal seam, gas extraction efficiency, and driving speed of the coal roadway significantly improve. Compared with hydraulic punching in the borehole with the ordinary drilling machine, the average speed of mining soft sub layers increased from 0.5 to 3.6 t/hour, the equivalent diameter of mining soft sub layers increased from 1.2 to 7.6 m, the average flow of gas extraction increased from 0.41 to 6.25 m^3/d, and the driving speed of the coal roadway increased from 123 to 211 m/month through the proposed method. The conclusions obtained in this study can provide reference to similar coal mining methods.

The creep time of the residual soft coal, the width of the residual soft coal, and the pressure of the directional jet significantly influence the effect of stress relief and permeability improvement under the geological conditions of Hudi Coal Mine. The effect of stress relief improved with the increase of creep time of the residual soft coal, the effect of stress relief reduced with the increase of the width of the residual soft coal, and the moderate pressure of the directional jet enhanced the efficiency of stress relief.

Declarations

Conflict of interest The authors declared that they have no conflicts of interest to this work. The authors declared that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.
Data Availability-Statement The data in the paper can be open and the readers can access the data just by the Journal's permission. Data sharing allows researchers to verify the results of an article, replicate the analysis, and conduct secondary analyses, so these are not any restrictions on data access. All the data used to support the findings of this study are included within the article.

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