

A study of mine water inrushes by measurements of in situ stress and rock failures

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Abstract This paper presents underground measurements (e.g., mini-frac tests) for in situ stress, hydraulic fractures, strata failures and hydraulic conductivity enhancement induced by coal extraction to study mechanisms of coal mine water inrushes. Mining perturbs the original state of in situ stress and results in stress redistribution. This causes rock failures and creates a water-conducting failure zone around a mining panel. If a confined aquifer is situated in the coal seam floor, the mining-induced stresses near the aquifer also generate hydraulic fractures in the rocks near to the aquifer. The mining-induced water-conducting failures and hydraulic fractures by the water pressure of the aquifer are the major reasons to cause water inrushes. The mining-induced water-conducting zone is obtained from theoretical studies and field measurements. The generating condition of the hydraulic fractures by the water pressure is also studied. Methods for predicting water inrushes are given based on the study of water inrush mechanisms. The mechanisms of water inrushes induced by faults are also analyzed from the case studies of water inrushes. It is of crucial importance to detect and map faults, paleo-sinkhole and other geological structures before mining. New mining methods are proposed for mining near confined aquifers to reduce the risks of water inrushes.

Keywords Water inrush · In situ stress · Coal mining · Confined aquifer · Strata failure · Hydraulic fracture

1 Introduction

Mining operations are threatened by various kinds of groundwater during coal extractions in China. Mine water inrushes from aquifers near mining coal seams occur frequently with disastrous consequences. There are three main possible water disasters affecting operation

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safety of coal mines in China: (1) water inrushes from Ordovician limestone underlying the Permo-Carboniferous coal seams in Northern China; (2) water inrushes from low Permian limestone underlying coal seams and from Triassic limestone overlying coal seams of late Permian in Southern China; and (3) water inrushes from Cenozoic porous aquifers in the Yellow River and Huai River alluvial plain areas (Zhang and Shen 2004). The most serious one of the three main types of possible water disasters affecting the safe operation of coal mines is the water inrushes from the Ordovician limestone under the Permo-Carboniferous coal seams in Northern China. The Ordovician limestone is a confined karst aquifer containing an abundant supply of water and a very high water pressure. Furthermore, the strata between coal seams and the aquifer are relatively thin. Due to these characteristics of the aquifer, plus mining-induced rock failures and inherent geological structures (such as water-conducting faults, fractures), high-pressure groundwater can break through the seam floors and burst into mining workings. Therefore, water inrushes from the aquifer occur frequently, and coal mines often suffer from serious water disasters during coal extractions.

There are many coal mines in China threatened by water inrushes from the Ordovician aquifer water (Zhang 2005). For instance, the maximum water inflow in a water inrush incident reached as much as 2053 m³/min (Yin and Zhang 2005) in a coal mine, causing the mine and other three nearby mines submerged in a very short time. There are still dozens of water inrush incidents taking place in China each year (e.g., 104 incidents in 2000 and 21 in 2013; Wu 2014), causing collieries to be submerged by water intrusions from the confined karst aquifers. Statistical results from the Chinese government show that the annual water discharges from China's coal mines were up to 7.17 billion m³ in 2012 (Wu 2014). Therefore, reducing water discharges, preventing and controlling mine water inrushes is still an important task. Various efforts for studying water inrush mechanisms have been conducted, and significant progress has been made (e.g., Zhang 1989; Li 1990; Zhang and Liu 1990; Gao and Li 1992; Zhang et al. 1997; Xiao and Xu 2000; Zhang et al. 2001; Yin et al. 2003; Yin and Wu 2004; Wu et al. 2004; Zhang 2005; Yin and Zhang 2005; Yang et al. 2007; Zhang et al. 2007; Guo et al. 2009; Yin 2009; Zhang et al. 2014; Ma et al. 2015). However, the mechanism of the water inrush is still not fully understood.

A mine water inrush happens when a high-pressure aquifer breaks through the surrounding rocks of the coal seam during mining and bursts into mining working face. Investigations of water inrush incidents show that the water inrushes from karstified aquifers underlying coal seams are primarily caused by the following three reasons: (1) mining causes rock failures and weakens the seam floor (Zhang et al. 1990), (2) high-pressure groundwater breaks through the weaken seam floor and bursts into mining workings (Zhang 2005) and (3) geological structures (such as water-conducting faults, fractures, karst paleo-sinkholes) make the floor even weaker (e.g., Zhang et al. 1997; Wu et al. 2004; Yin and Zhang 2005). Therefore, to evaluate the risks of water inrushes, it is necessary to investigate in situ stress and rock failures induced by mining and the aquifer.

2 Underground measurements of in situ stress and mining-induced hydraulic fractures

In situ stress measurements have been extensively conducted to investigate stress states of underground rocks. The in situ stress includes three mutually orthogonal principal stresses in the subsurface (e.g., Meng et al. 2011), i.e., the vertical (overburden) stress (σ_v), the maximum horizontal and minimum horizontal stresses (σ_H , σ_h). In situ stress is normally

measured from borehole mini-frac or hydraulic fracturing tests (e.g., Haimson and Fairhurst 1967). Different from conventional methods, we used underground boreholes in a roadway to perform mini-frac tests for the rocks underlying the coal seam and water pressure in the aquifer. The tests were conducted in Feicheng coal field of Shandong Province in China.

2.1 The minimum stress measurements from the mini-frac tests

The minimum horizontal stress can be determined by the commonly accepted method of micro-hydraulic fracturing (e.g., Haimson and Cornet 2003) or mini-frac. The minimum stress in a normal faulting stress regime is the minimum principal horizontal stress (Peng and Zhang 2007). This stress is typically equal to the fracture closure pressure, which can be observed after shut-in on the decline curve of a mini-frac test (Zhang and Roegiers 2010). Figure 1 schematically presents a typical mini-frac test with two pressurization cycles.

In situ stress measurement in an underground mine is different from the conventional measurement. Boreholes need to be drilled in underground roadways. In each mini-frac test, a borehole interval is isolated and sealed with two inflatable packers; i.e., only the rocks between of the two packers are exposed to the high-pressure fluid pumped at a constant rate. The pressure increase in the tested rock is typically linear as long as there are no leaks in the system, and the exposed rocks are not highly permeable. At some point, the rate of pressurization changes such that the pressure–time curve departs from linearity. This departure from linearity is referred to as the fracture initiation pressure (p_i), as shown in Fig. 1. The pressure is then typically seen to increase at a lower rate until a maximum pressure, the breakdown pressure (p_b), is reached. The fracture breakdown pressure caused by water injection can be obtained from the following equation (Haimson and Fairhurst 1967; Zhang 2011, 2013):

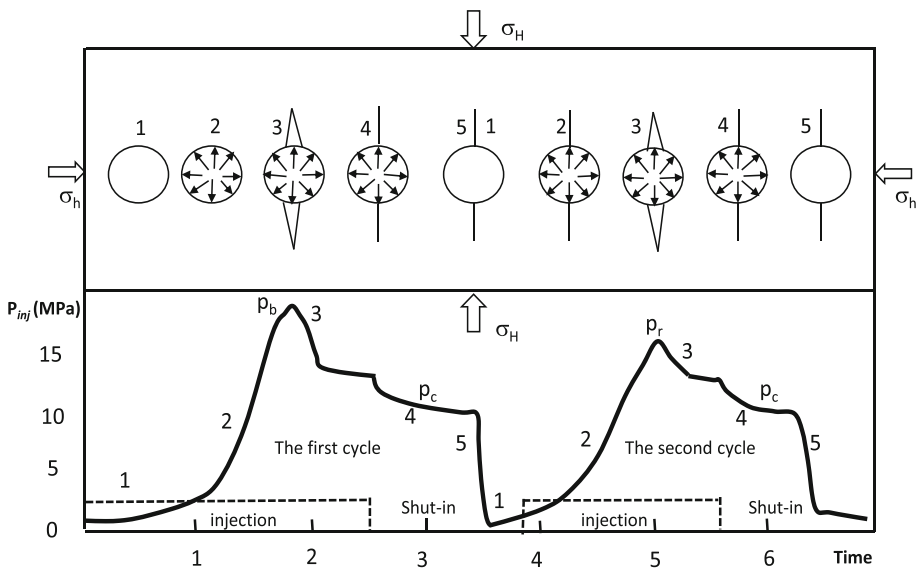


Fig. 1 Schematic plot of the pumping pressure, fracture growth and time or volume of injected fluid in a mini-frac test with two injection cycles

$$p_b = 3\sigma_{\min} - \sigma_{\max} - p_p + T_0 \quad (1)$$

where p_b is the breakdown pressure; $\sigma_{\min} = \sigma_h$, $\sigma_{\max} = \sigma_H$ are the minimum horizontal stress and the maximum horizontal stress for vertical boreholes, respectively; p_p is the pore pressure in the rock; T_0 is the tensile strength of the rock.

After the rock is broken down (hydraulic fractures created), at some point, the pressure in the borehole remains fairly constant (p_{prop}) at the same flowrate, and the fracture is propagating. When the pumps are turned off, the pressure immediately drops to the instantaneous shut-in pressure (p_{isip}). After the well is shut-in, the pressure begins to decline as the fracture starts to close; the pressure acting to close the fracture is equal to the minimum horizontal stress (σ_h); i.e.,

$$\sigma_h = p_c \quad (2)$$

where p_c represents the closure pressure.

A second pressurization cycle can be performed to obtain more data. Because a fracture has been created by the first cycle, there should be no tensile strength in the fracture reopening; i.e.,

$$T_0 = p_b - p_r \quad (3)$$

where p_r is the fracture reopening pressure.

2.2 The maximum horizontal stress estimates from the mini-frac tests

The minimum horizontal stress and tensile strength can be obtained from a mini-frac test; then, the maximum horizontal stress in both impermeable and permeable cases can be calculated from the breakdown pressure using Eq. (1). The maximum horizontal stress for impermeable formations can be estimated from the mini-frac test in a vertical borehole using the following elastic solution:

$$\sigma_H = 3\sigma_h - p_b - p_p + T_0 \quad (4)$$

Detournay and Cheng (1988) proposed a poroelastic solution for breakdown pressure induced by pressurization of a borehole in hydraulic fracturing in a permeable formation. The maximum horizontal stress in permeable formations can be derived from it as the following form in a vertical borehole:

$$\sigma_H = 3\sigma_h - 2(1 - \eta)p_b - 2\eta p_p + T_0 \quad (5)$$

where η is a poroelastic coefficient ranging from 0 to 0.5 and $\eta = \alpha(1 - 2\nu)/[2(1 - \nu)]$, α is the Biot coefficient; ν is the drained Poisson's ratio.

2.3 In situ stress and mini-frac tests in underground boreholes

Three boreholes (D1, D2 and D3) were drilled in underground roadways in Feicheng coal mine. These holes were used for both in situ stress measurements prior to mining and rock failure observation post-mining. We here only show some results in Hole D1. The top of Hole D1 was at the level of -547.9 m (burial depth of 644.9 m) and situated in the floor strata of the coal seam no. 7. The total depth of the hole was 73.72 m. The formations incline gently with a dip angle of 16° , as shown in Fig. 2. Hydraulic fracturing tests were performed by injecting high-pressure water into the interested sections to measure in situ

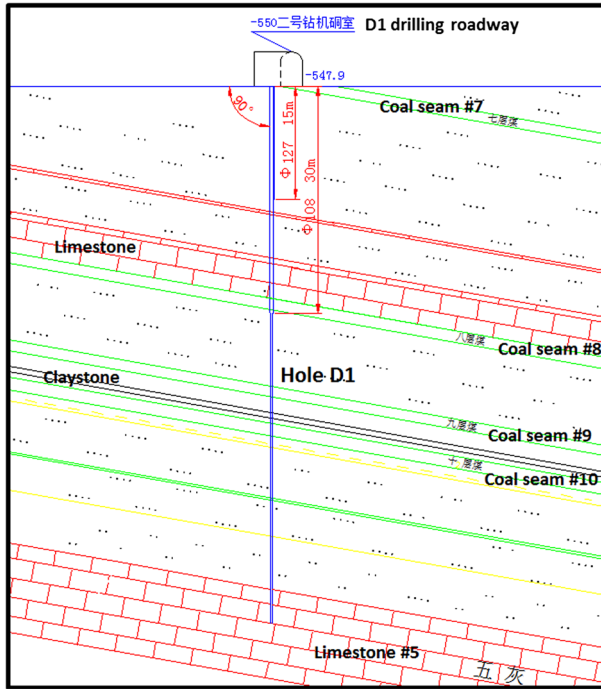


Fig. 2 The cross section and lithologies of the underground observation borehole, D1

stress and rock failures induced by hydraulic fracturing. In each test interval, 4–5 injection cycles were conducted to obtain reliable data, and there were 8 tests successful in Hole D1.

Figure 3 presents a mini-frac test conducted in 10.10–10.8 m below the top of the Hole D1. The rock in this section was siltstone, and 5 injection and shut-in cycles were performed in the test. It followed the procedure described in Sect. 2.2. Figure 3 shows that it has an obvious breakdown of the formation when the injection pressure reaches to 16.2 MPa (i.e., $p_b = 16.2$ MPa); then, the pressure drops because the injected fluid flows into the newly created fractures. After the injection pump is shut-in, the pressure declines and the fractures close gradually. When the pressure reaches closure pressure (p_c) or the minimum horizontal stress (σ_h), the current cycle of the test finishes and next cycle starts by repeating the previous steps. From the breakdown, closure and reopen pressures, the horizontal stresses and tensile strength can be estimated from Eqs. 2–5.

Comparing the mini-frac tests in different rocks, we found that behaviors of hydraulic fracturing and in situ stress of the rocks depend highly on the lithologies. That is, the breakdown pressure, closure pressure and minimum horizontal stress gradient are very different for siltstone, claystone and sandstone (refer to Figs. 3, 4, 5; Table 1). The sandstone or siltstone has a higher tensile strength than the shale. That is one of the reasons why the sandstone or siltstone has a larger breakdown pressure than the shale; i.e., the sandstone or siltstone is harder to be broken down in this area. However, the claystone has a higher horizontal stress gradient than the sandstone or siltstone. This means that once the rock is broken down, the sandstone or siltstone needs a smaller water pressure than that in the claystone or ductile rock to keep the fracture open because of it has a smaller minimum stress gradient (S_h).

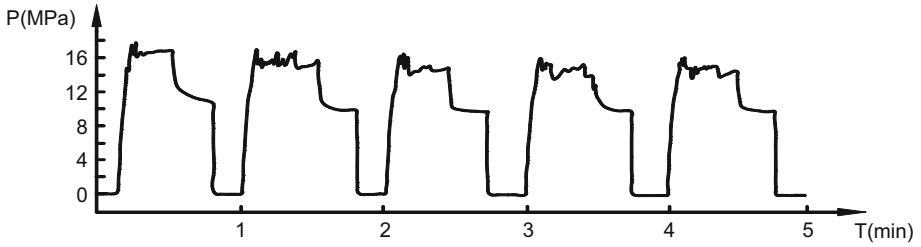


Fig. 3 Pumping pressure versus test time in a siltstone at the depth of 10.1–10.8 m from the top of the borehole D1 in a mini-frac test with five injection cycles

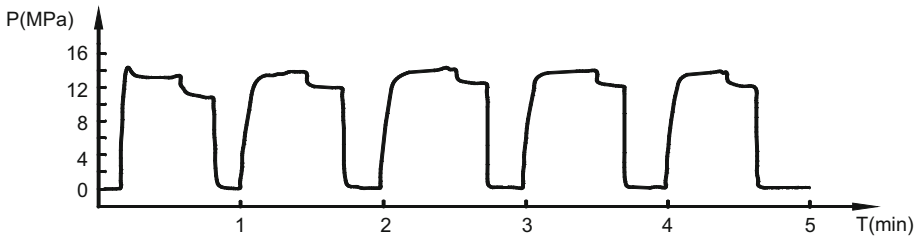


Fig. 4 Pumping pressure versus test time in a claystone at the depth of 49.77–50.47 m in D1

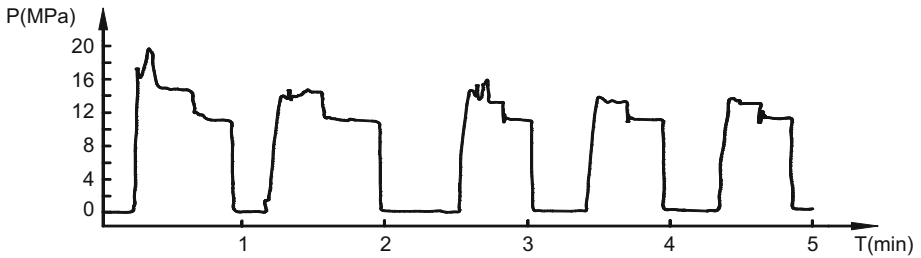


Fig. 5 Pumping pressure versus test time in a medium-grained sandstone at the depth of 61.5–62.2 m in D1

Table 1 The breakdown pressures, closure pressures and minimum horizontal stress gradients in different rocks

Depth from the surface (m)	p_b (MPa)	p_r (MPa)	σ_h (MPa)	S_h (MPa/m)	Estimated T_0 (MPa)	Lithology
655.3	16.2	14.3	10.3	0.0157	1.9	Siltstone
694.9	14.9	13.7	12.5	0.018	1.2	Claystone
706.9	19.2	14.2	11.82	0.0167	5.2	Sandstone

It should be noted that the mentioned rocks are the rocks without pre-existing fractures, for those with pre-existing fractures, the breakdown pressures and tensile strengths are much lower than the intact rocks.

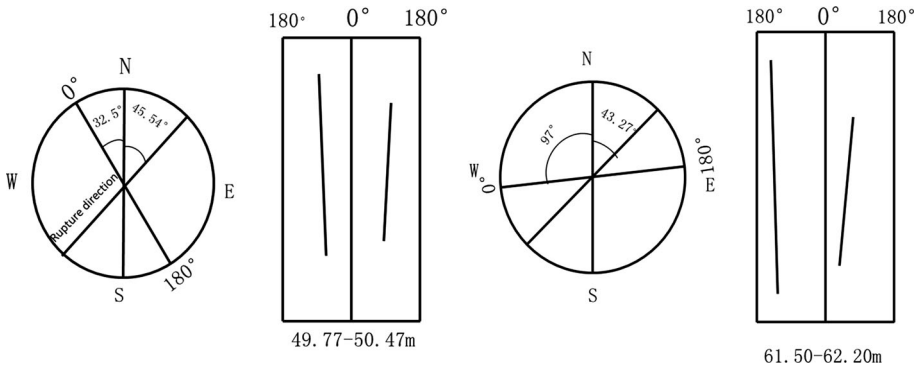


Fig. 6 Orientations of the observed hydraulic fractures in Hole D1 injection test in two depth intervals

The mini-frac tests can also be used to evaluate rock failure owing to the water pressure, which is similar to study the rock hydraulic fracturing caused by high fluid pressure from the aquifer. Figure 6 shows the orientations of the downhole-observed hydraulic fractures in Hole D1 after the hydraulic fracturing tests. The hydraulic fractures were vertical fractures, implying that the vertical stress was the maximum in situ stress or this area was not located in a high tectonic stress regime.

From Fig. 6, the orientation of the maximum horizontal stress can be obtained (i.e., in N43.3°–45.5°E direction), which is the propagation direction of the hydraulic fractures. It can be inferred that when the water pressure of the confined aquifer is higher than the rock breakdown pressure (refer to Eq. 1), the hydraulic fractures will be created by the water pressure of the aquifer and may penetrate into the floor rocks for certain distances to weaken the coal seam floor. It should be noted that from Eq. 1, the breakdown pressure or the pre-condition of creating new hydraulic fractures depends on several factors, such as the minimum and maximum horizontal stresses and tensile strength of the rock. This can affect the generation of new fractures in the coal seam floor in the following two aspects. Firstly, if there are faults or other fractures existed in the coal seam floor, the reduced tensile strengths by the faults and fractures will make the hydraulic fractures be much easier to create. This will increase the rock failures and create a potential for water inrushes. Secondly, during and after coal mining, the stresses around the mining panel will redistribute. This will cause the breakdown pressure changes and might create new hydraulic fractures, which will be discussed in the following section.

2.4 Conceptual model of hydraulic fractures caused by mining

Mining perturbs the original stress state in the rocks surrounding the mining panel and results in a stress redistribution. Mining-induced stress redistribution causes the vertical stress to increase in the abutment area of the seam floor (i.e., the unmined area near the mining panel). The higher vertical stress at the abutment is mainly caused by the transfer of the weight of the overburden roof strata in the excavated area to the unmined area. This high stress causes compressions of the rocks in the seam floor beneath the abutments. However, the vertical stresses decreases in the seam floor beneath the mined area; therefore, the floor strata experience a state of unloading in which the mining-induced tensile fractures are developed easily (Zhang and Shen 2004; Zhang 2005). This mining-induced stress changes may also cause the hydraulic fractures, when a confined aquifer is situated in

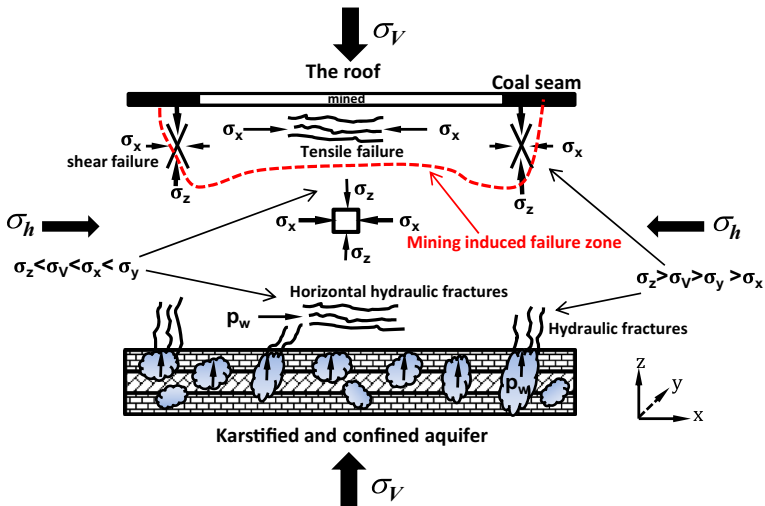


Fig. 7 Schematic stress changes and fractures induced by mining and water pressure in a cross section of a mining panel

the seam floor. Because of the vertical stress reduction and changes in the horizontal stresses, it causes the far-field stress change near the aquifer (refer to Fig. 7). In a cross section of mining panel in Fig. 7, in situ stress prior to mining is assumed to be $\sigma_v \geq \sigma_H \geq \sigma_h$ and the direction of σ_H perpendicular to the paper. As mining advances, changes of stresses, particularly the vertical stress in the floor strata, include the stress increase in unmined area and the stress decrease in mined area. Beneath the mined area, the floor experiences expansion and the stress relaxation; therefore, the rocks are more prone to creation of tensile fractures. However, in the transition area between the floor compression (stress increase) and expansion (stress decrease), the rocks are more likely to create shear fractures. Figure 7 demonstrates that after mining, it creates tensile failures in the seam floor beneath the mined area due to unloading, but shear failures near the abutment area due to high vertical stress (refer to the next section). The hydraulic fractures may also be created by the stress reduction in the rocks beneath the mined area if a confined aquifer exists. Once the water pressure in the aquifer exceeds the fracture breakdown pressure (as shown in Eq. 1), the hydraulic fracture will be generated and propagated. Because the vertical stress is reduced and become the minimum stress (less than the two horizontal stresses) in the rocks beneath the mined area, it will generate horizontal hydraulic fractures, because the hydraulic fractures are generated in the directions perpendicular to the minimum stress (Hubbert and Willis 1957). The condition to generate the horizontal hydraulic fractures can be obtained by modifying Eq. 1:

$$P_w \geq 3\sigma_z - \sigma_y - p_p + T_0 \tag{6}$$

where P_w is the water pressure in the confined aquifer; σ_z , σ_y are the stresses in z and y directions after mining and $\sigma_y \geq \sigma_z$; p_p is the pore pressure in the rocks of the floor, for relatively impermeable rocks, p_p can be ignored. The tensile strength of the rock, T_0 , is also

negligible, particularly for fractured rocks. Therefore, the following simplified equation can be obtained:

$$P_w \geq 3\sigma_z - \sigma_y \tag{7}$$

The horizontal hydraulic fractures are mainly formed in the rock below the mined area and above or near the aquifer, where the rock has much lower vertical stress (σ_z) caused by mining compared to the overburden stress (σ_v) prior to mining (Fig. 7).

However, because of the high abutment stress effect, the vertical stress (σ_z) becomes greater than the overburden stress (σ_v) and is the maximum stress in the floor below the unmined area. Therefore, the vertical or near-vertical hydraulic fractures may be generated by the water pressure (as shown in Fig. 7), when the following stress state is reached:

$$P_w \geq 3\sigma_x - \sigma_y \tag{8}$$

where $\sigma_y \geq \sigma_x$.

When the hydraulic fractures (near the aquifer of the floor) connect to the mining-induced failure zone (shear and tensile failures caused by mining just below the mining area and will be discussed in the following section) as shown in Fig. 7, water from the aquifer will intrude into the mining area and cause water inrushes. Therefore, decreasing mining-induced rock failures and hydraulic fractures can reduce risks of water inrushes.

3 Mining-induced strata failures and permeability enhancement

3.1 Underground measurements of mining-induced water-conducting failure zone

Coal extraction causes strata failures and enhances permeability or the hydraulic conductivity in the surrounding strata of a mining panel. To measure the conductivity variation in the underlying strata induced by mining, boreholes need to be drilled pre-mining in

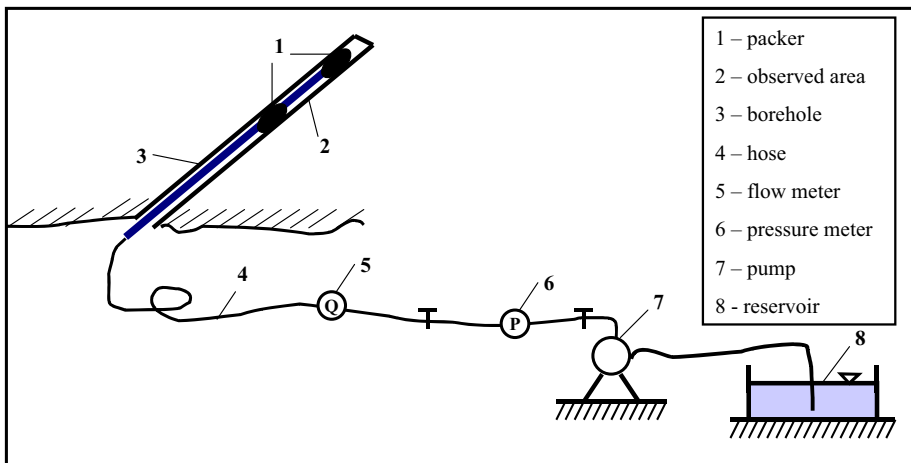


Fig. 8 Schematic water injection to measure hydraulic conductivity of the rocks induced by mining in an underground borehole

Fig. 9 Water injection rate versus the advance of the mining face in a coal mine. In the figure, the negative distance represents pre-mining state, and the positive means post-mining

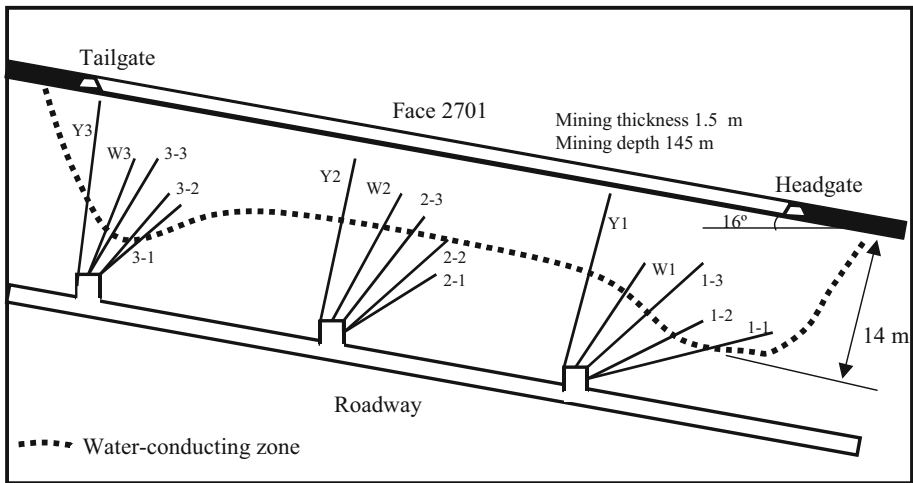
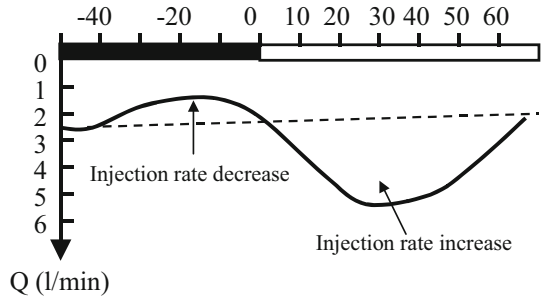


Fig. 10 Observed permeability enhancement or the water-conducting failure zone in the underlying strata of the slightly inclined coal seam in Fengfeng coal mines, Hebei Province

underground roadways. In each borehole, water injection and a number of well logging techniques can be used to determine rock properties, borehole fissures and changes of hydraulic conductivity. Figure 8 shows a schematic view of a water injection instrument. The key technique during measurements is to control the injection pressure. The pressure should not be high enough to create new fractures in the strata, because the experiment is to determine the changes in hydraulic conductivity induced by mining. Therefore, the injection pressure should not exceed the minimum principal stress of the surrounding strata.

In the measurements, boreholes need to be drilled in the underground roadway prior to mining. Then, the water injection instrument (e.g., Fig. 8) is applied to measure the flowrate of water injection pre- and post-mining. The water injection along each borehole is conducted by pumping water into the borehole. The measurements of flowrates of water injection are taken in each hole at different sections throughout the borehole and at different mining times (Zhang 2005). After analyzing the measured pre-mining and post-mining flowrate of water injection in each borehole, the zone of the permeability increments caused by mining can be identified, as shown in Fig. 9. According to the injection rates, the water-conducting zone can be determined. Figure 10 presents the shape and area of the water-conducting zone or permeability enhancements caused by mining in

Wangfeng coal mine, Hebei Province of China. It shows that the water-conducting capacity increases in the floor strata because of coal extraction, and the closer the strata is to the extracted seam, the higher the permeability increment in the seam floor.

Underground measurements have shown that characteristics of rock failures and permeability enhancements in the floor strata are considerably different for different inclinations of the extracted seams. For flat or slightly inclined seams (inclination angle, $\alpha < 25^\circ$), the profile of the water-conducting failure zone is broad in section with extended lobes, and the maximum failure depth occurs beneath the headgate and tailgate, respectively, shown in Fig. 10. However, for inclined seams ($25^\circ < \alpha < 60^\circ$), the failure zone propagates downwards in an asymmetric manner in the dip direction; the extent of the failure zone or the water-conducting zone increases gradually from updip to downdip (Zhang 2005).

3.2 Estimates of the depth of the water-conducting failure zone

According to in situ observations, a number of parameters affect the development and depth of the water-conducting failure zone. Mining width of the working face and uniaxial compressive strength of the strata are the most important of all parameters. An empirical equation for predicting the depth of the water-conducting failure zone was developed from underground measurement results in long-wall and short-wall mining faces (Zhang and Liu 1990). The equation can be expressed as:

$$h_1 = 0.303L_x^{0.8} \tag{9}$$

where h_1 is the depth of the water-conducting failure zone starting from the immediate floor of the seam (m); L_x is the mining width of the mining face (m).

Note that the observing data were obtained from coal mines in Northern China with mining depths ranging from 103 to 560 m and uniaxial compressive strengths from 20 to 40 MPa. The new observation data verified the above equation.

Many efforts have been made to predict the mining-induced failure area as an approximation of the water-conducting failure zone. These include theoretical analysis as well as numerical simulation. According to the rock mechanics and plastic sliding theory, Zhang and Liu (1990) proposed the following equations to calculate the maximum depth of failure zone induced by mining in the seam floor:

$$h_1 = \frac{(n + 1)H}{2\pi} \left(\frac{1}{\tan \varphi} - \frac{\pi}{2} + \varphi \right) - \frac{c}{\gamma \tan \varphi} - mH \tag{10}$$

where h_1 is the maximum depth of failure zone; H is the burial depth; n is the ratio of the abutment stress to the overburden stress; m is the ratio of the vertical stress in the mined area to the overburden stress; φ , c are the angle of the internal friction and cohesion of the strata, respectively; γ is the average unit weight of the strata. And,

$$h_1 = \frac{x_a \cos \varphi}{2 \cos\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)} e^{\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) \tan \varphi} \tag{11}$$

where x_a is the length of failure zone of the coal seam around the mining face, which can be calculated from Zhang et al. (1997); e.g., one empirical equation is $x_a = 0.015H$. Using Eqs. 9–11, the water-conducting failure zone can be estimated. These equations have found applications in coal mines (e.g., recently case application reported by Xu et al. 2014).

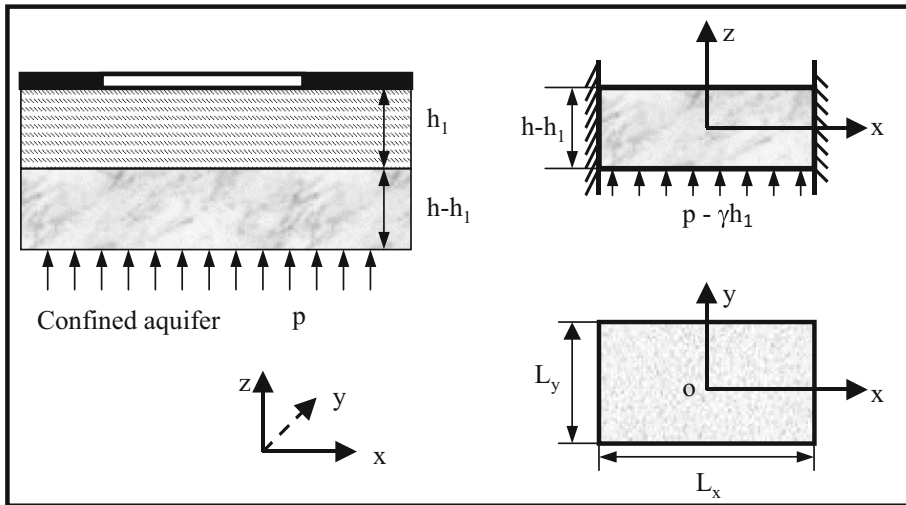


Fig. 11 Two zones are assumed in the coal seam floor for studying water intrushes

4 Mechanisms and predictions of water intrushes

Two categories of water intrushes can be classified for the purpose of studying mechanisms of mine water intrushes. They are (1) water intrushes in the intact strata condition without faults and geological structures and (2) water intrushes with faults or paleo-sinkholes in the floor strata.

4.1 Mechanisms and predictions of water intrushes in the intact strata

Two zones can be normally assumed in the coal seam floor in terms of studying water intrushes and rock failures induced by mining. The first zone is the rock failure zone or water-conducting zone caused by mining (refer to Figs. 10, 11). The rocks in this zone are the rocks with mining-induced failures or fractures (e.g., shear and tensile failures) and become water-conducting. If an aquifer exists in this zone, water will flow into the mining area. The second zone is the intact rocks below the water-conducting zone and above the confined aquifer or above the hydraulic fracture zone if it exists (as shown in Fig. 7). The intact rock zone acts as a plate exerted by the water pressure. When the intact rock zone fails because of mining and the loading from the water pressure and the induced fractures connect to the water-conducting zone, water from the aquifer will intrude into the mining area causing water intrush.

4.1.1 Empirical method of water intrush prediction

According to the field data of water intrushes from coal mining faces, there are two most significant parameters affecting water intrushes from an underlying confined aquifer, i.e., the water pressure of the confined aquifer and the thickness between the coal seam and the aquifer. By analyzing the field data of water intrush incidents in different coal mines of China (data from one of the coalfields are shown in Fig. 12), an empirical relationship

Fig. 12 The calculated critical water pressure versus the thickness of the floor compared to the mining faces with and without water intrushes in Jiaozuo Coal Mine Area, Henan Province

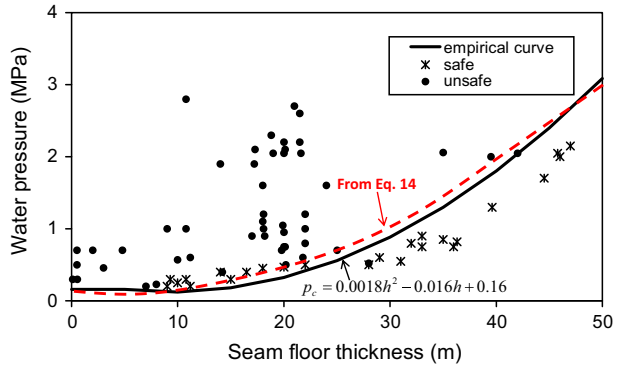


Table 2 Parameters in Eq. 12 for predicting the critical water pressure p_c in some coal mines in China

Coalfield	A	B	C
Fengfeng	0.0006	0.026	0
Jiaozuo	0.0018	-0.016	0.16
Lianshao	0.014	-0.0836	0
Heishan colliery, Zibo	0.00177	0.015	-0.43
Shigu and Xiazhuang collieries, Zibo	0.0016	0.015	-0.3
Hongshan and Zhaili collieries, Zibo	0.002	0.015	-0.158
Shuangshan and Fucun collieries, Zibo	0.00084	0.015	-0.168

between the critical water pressure and the thickness of the strata from the coal seam to its underlying aquifer can be obtained. It can be expressed as the following generalized form:

$$p_c = Ah^2 + Bh + C \tag{12}$$

where p_c is the critical water pressure (MPa); h is the thickness of the strata between the coal seam and its underlying aquifer (m); A , B and C are the coefficients depending on the strata lithology (Table 2). The empirical equation has played an important role for water intrush prediction in coal mines with similar geological and mining conditions.

4.1.2 Theoretical method of water intrush prediction

We modify the theoretical model for analyzing the floor strata given by Zhang (2005). The elastoplastic plate model was applied to analyze the stresses and failures of the intact strata (Fig. 11). The derived relationships are similar to the empirical equation (Eq. 12), but with more parameters are considered, such as the critical water pressure, rock mechanical parameters and mining size:

$$p_1 = A_1(h - h_1)^2\tau_0 + \gamma h, \tag{13}$$

$$p_2 = A_2(h - h_1)^2S_t + \gamma h, \tag{14}$$

where p_1, p_2 are the critical or maximum water pressures that strata can bear; h is the distance between the seam and the underlying aquifer; h_1 is the depth of water-conducting failure zone in the floor, which can be obtained from Eqs. 9–11; γ is the unit weight of the floor strata; τ_0, S_t are the strata shear and tensile strengths, respectively; and

$$A_1 = \frac{\pi^2 [3(L_x^4 + L_y^4) + 2L_x^2 L_y^2]}{6L_x^2 L_y^2 (L_x^2 + \nu L_y^2)}, \quad A_2 = \frac{12L_x^2}{L_y^2 (\sqrt{L_y^2 + 3L_x^2} - L_y)^2}$$

where ν is Poisson's ratio and L_x, L_y are the mining width and length, respectively.

If the critical pressure, calculated in Eq. 13 or 14, is greater than the actual water pressure in the aquifer, then no water inrush occurs during mining. The criteria for no water inrush can be obtained from Eqs. 13–14 and be expressed as:

$$A_1(h - h_1)^2 \tau_0 + \gamma h \geq p, \quad (15)$$

$$A_2(h - h_1)^2 S_t + \gamma h \geq p, \quad (16)$$

where p is the actual water pressure in the underlying aquifer.

The above equations have been applied to predict water inrushes in some coal mines in Northern China. By analyzing the water inrush data, strata strength parameters, and by combining the empirical formulas for different coal mines (Eq. 12), the prediction equations (Eqs. 13–16) have a good prospect to predict water inrushes and guide mining design. These equations were also validated by 111 mining faces extracted over confined aquifers (72 water inrush cases, Zhang et al. 1997) in Northern China. Figure 12 presents the calculated results in Jiaozuo Coal Mine Area by applying Eq. 14 with $S_t = 0.6$ MPa, $\gamma = 0.023$ MPa/m. A mining size of $L_x = 140$ m and $L_y = 50$ m is used, and the calculated results are compared to the water inrush data in the coal mines. It can be seen that the proposed model gives an excellent match to the field results.

4.2 Water inrush mechanisms with effects of faults and paleo-sinkholes

4.2.1 Water inrush mechanism with effects of paleo-sinkholes

The karst paleo-sinkhole is a special geological structure widely found in the coal measures of Northern China. Some paleo-sinkholes are hidden in the strata of coal beds changed hydrogeological conditions, and some of them have high permeability and connectivity, making them excellent connectors between the karst aquifer and the coal seams. Consequently, during coal extraction, the disastrous water inrushes take place frequently, which have caused severe losses not only in mine submersions and personnel casualties, but also in environmental quality. When a permeable paleo-sinkhole exists in the floor strata, the effective distance between the aquifer and the coal seam is reduced greatly. This makes it easier for groundwater to intrude into the mining working area, as shown in Fig. 13. The paleo-sinkhole also changes the structure of the floor strata by becoming a discontinuity. This in turn increases the strata failure in the seam floor (Yin and Zhang 2005). Additionally, with the effect of water pressure, the floor strata above the top of the paleo-sinkhole may generate tensile fractures by hydraulic fracturing. To reduce water inrushes from the paleo-sinkholes, correctly mapping paleo-sinkholes are necessary for mining design.

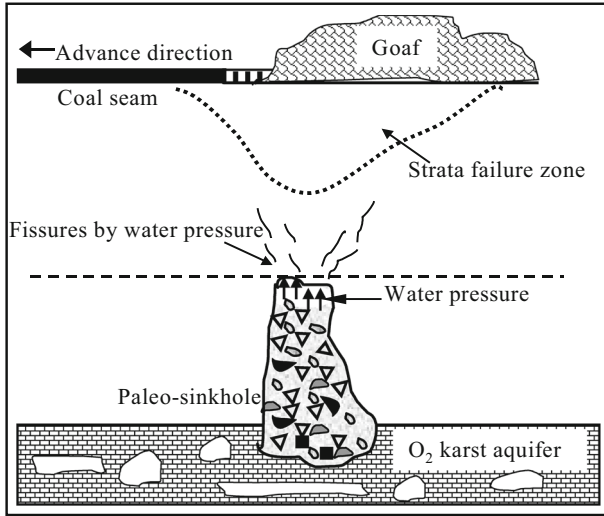
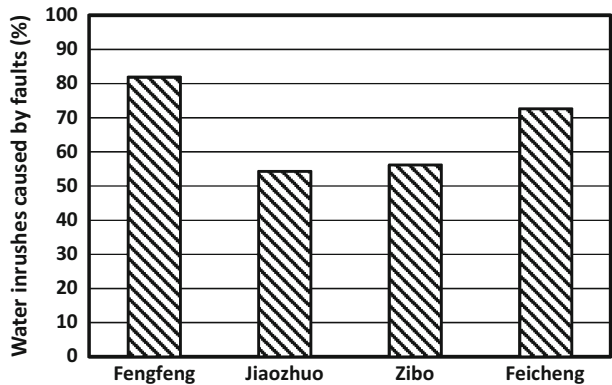


Fig. 13 The strata failures in the seam floor caused by the paleo-sinkholes and coal mining

Fig. 14 Percentage of water intrushes caused by faults in 163 water intrush incidents in 4 coal mine areas in Northern China



4.2.2 Water intrush mechanism with effects of faults

The geological structures, particularly faults, are one of the main causes of water intrushes (Zhang 2005). Statistical results in 163 water intrush incidents of the long-wall mining faces in Northern China indicate that most water intrushes (106 over 163 cases) from underlying aquifers were related to faults (Fig. 14). The following explanation may be applied to analyze this phenomenon. First of all, the rock strength in the fault zone is much lower than that of normal rocks; therefore, rocks in the faulted zones fail easier and create a larger failure zone. Secondly, existence of a fault may reduce the distance between the seam and the aquifer. Thirdly, if the faulted zone is permeable and reaches to the aquifer, it will cause water intrush once the fault is unveiled by mining. Based on water intrush incidents from China’s coal mines, the following conceptual models of water intrushes from faults are summarized.

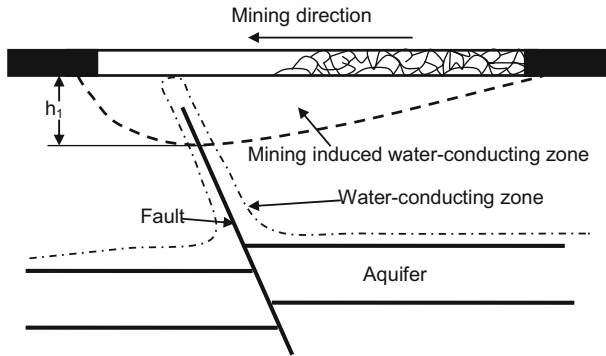


Fig. 15 Water inrush caused by a fault cutting through almost the entire floor

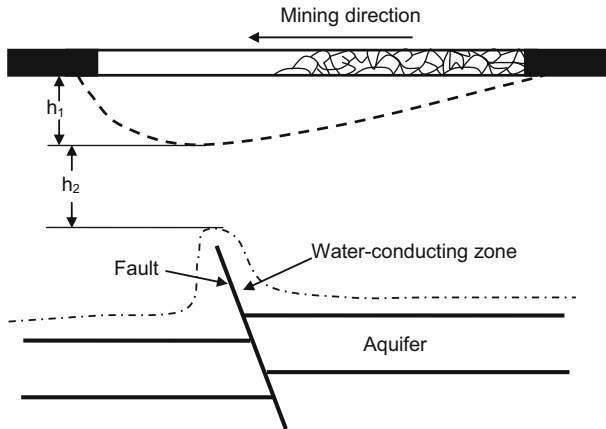


Fig. 16 Water inrush caused by a fault cutting through the bottom of the floor

1. Faults cutting through most of the floor

If a fault cuts through most of the floor (refer to Fig. 15) and the faulted zone is permeable, the water inrush will happen once the mining-induced fractures connected to the fault. Even if the faulted zone is impermeable, mining and water pressure may reactivate the fault (or create shear slipping along the fault) causing water inrushes.

2. Faults cutting through the bottom of the floor

If a fault only cuts through the bottom of the floor, as shown in Fig. 16, and the faulted zone is permeable, the water will flow into the floor rocks and reduce the distance from the seam to the aquifer. In this case, there is still an intact rock zone (h_2) between the mining-induced water-conductive zone and the fault. Whether the intact rocks can bear the water pressure or not, it is the key for preventing water inrushes. The required thickness of the intact rocks for preventing water inrushes can be evaluated by using Eqs. 13–16.

3. Faults cutting through the top of the floor

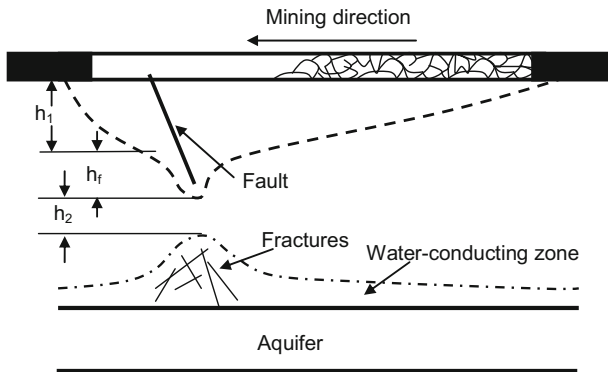


Fig. 17 Water inrush caused by a fault cutting through the top of the floor

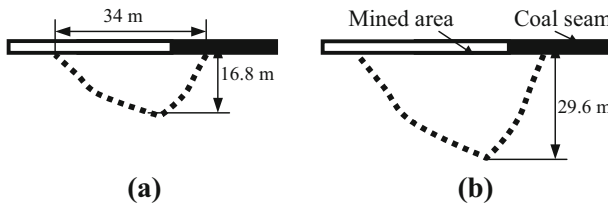


Fig. 18 Measured water-conducting zone in the floor caused by mining in the mining direction in the Huainan coalfield. **a** Normal geological condition. **b** In the faulted rocks

If a fault only cuts through the top of the floor (refer to Fig. 17), this is a less risky case for water inrushes than the previous two cases. The fault cutting through only the top of the floor causes a larger mining-induced failure zone or a larger water-conducting zone beneath the mining area (Zhang 2005; Yin and Zhang 2005), as shown in Fig. 18. In situ measurements in the Huainan coalfield show that the maximum depth of the water-conducting zone in the floor was 16.8 m for the normal case (Fig. 18a). However, it was 29.6 m in the faulted zone (Fig. 18b). This indicates that a fault existed in the seam floor makes the strata more susceptible to failure.

To avoid water inrushes from faults, the first step is to map the faults before mining; secondly investigate the potentials of water inrushes from the faults; then apply appropriate methods to reduce the risks of water inrushes. For example, water-proofing barriers need to be left for large faults. For small faults and fractures, grouting can seal them, consolidate the weak rocks and reduce the possibility of water inrushes, and it has been applied in some coal mines (e.g., Xu et al. 2014).

5 Conclusions

The mini-frac tests show that the breakdown pressure, closure pressure and minimum horizontal stress gradient are different for siltstone, claystone and sandstone. The sandstone or siltstone has a higher tensile strength than the shale. That is one of the major reasons why the sandstone or siltstone has a larger breakdown pressure than the shale; i.e., it is

harder to be broken down in this area. However, the claystone has a higher horizontal stress gradient than the sandstone or siltstone.

Mining perturbs the original stress state and results in the stress redistribution. The stress redistribution causes the vertical stress to increase in the abutment area of the seam floor and decreases in the mined area of the seam floor. These induce rock failures in the floor, and the rocks form a water-conducting zone beneath the mining panel. If a confined aquifer is situated in the seam floor, the mining-induced stress concentration around the aquifer may create hydraulic fractures in the rocks near to the aquifer. The mining-induced water-conducting failures and hydraulic fractures are the main reasons for water inrushes.

Empirical and theoretical methods for predicting water inrush are given and have been verified. When mining above confined aquifers has water inrush potentials, mining design needs be modified, and new mining methods should be adopted. The new methods, such as short-wall mining, room-and-pillar or strip-and-pillar mining and long-wall mining with backfilling, can effectively minimize mining-induced failures and reduce the water-conducting zone.

Water inrush incidents have shown that most water inrushes from the underlying aquifers were related to faults. Therefore, it is of crucial importance to detect and map faults and other geological structures prior to mining. Water inrush risks are dependent on the locations of faults. If a fault cuts through the entire seam floor and the aquifer, it is the most likely case to occur water inrushes. For large faults, water-proofing barriers need to be left. For small faults and natural fractures, grouting can seal them and reduce the possibility of water inrushes.

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