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Experimental study on floor failure of coal mining above confined water

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Abstract
Water inrush accidents were currently one of the most frequent forms of disaster in coal mines where the mining seams were above a major acquirer with high pressure water. Understanding the fracturing process of mining floor under the effect of highly pressurized water underneath was essential for preventing water inrush. A testing system simulating such cases was developed. This system is comprised of a simulation test bed, a confined water loading system, and a computer monitoring system. A 1900 mm (L) × 220 mm (W) × 1800 mm (H) physical model was constructed, excavated, and monitored using the testing system. The system displayed the development process of floor fractures and the formation of water inrush channels. Based on the stress distribution, the floor rock strata can be divided into five zones, stress stable zone, stress recovery zone, stress reduction zone, stress increase zone, and in situ stress zone. Overall, the floor was in a state of high shear stress under the action of rock stress and high pressure confined water, which was likely to cause shear fracturing and consequently possible water inrush into the mine working faces.

Introduction

Hydro geological conditions in mining areas are complex and several serious water inrush accidents had occurred during underground mining and tunnel excavation in China. Incomplete statistics indicate that more than 250 mines were flooded in the past 20 years, which resulted in approximately 2000 fatalities and a total of economic losses of 35 billion yuan (US$5.2B). A part of major water inrush accidents occurred in China coal mines as shown in Table 1. Floor water inrush, as a major form of mine disaster, was an important subject of research in the field of mine safety (Hu et al. 2014; Miao et al. 2008; Sun et al. 2011; Sun et al. 2013). Physical simulation test was one of the commonly used research methods in the laboratory. In the previous studies, special hydraulic equipment that simulated Ordovician limestone was designed to achieve the first physical simulation of fault-to-floor water inrush in China (Yang and Li 1997). A group of

springs was installed in the bottom of a two-dimensional (2D) physical model to simulate aquifer damage during mining (Xu et al. 2013). A layer composed of 36 springs with specific stiffness was used to simulate displacements of floor strata at different depths (Zhao et al. 2013). A water pressure-loading system from a confined aquifer to coal seam was developed to analyze the water inrush risk. In this system, a specific pressure was maintained by adding water into water bags simultaneously. The water bag may fracture the water-resisting layer after the coal seam has been excavated; however, the water inrush phenomenon cannot be identified from the system due to the lack of real water flow in the fractures (Feng et al. 2009). A new system of a coupled solid–fluid model was used to simulate the quasi-three-dimensional plane stress and plane strain conditions (Li et al. 2013a; Li et al. 2010). A larger physical modeling system for high pressure floor water was developed to simulate the unique problems of deep mining by Sun and Zhang (2015). The aquifer was simulated by 96 holes in the tank in this system. However, this test system required exact material strengths to be maintained and good sealing. In addition, many scholars studied the floor water inrush using models and numerical simulation method (Zhang et al. 2016; Li et al. 2013b; Cao et al. 2016; Shi et al. 2014; Shi et al. 2013; Xu and Li 2014; Hang et al. 2009; Li et al. 2013c; Zhang 2005; Guo et al. 2012). Some researchers had developed coupled

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Table 1   Statistics of water inrush accidents occurred in the China coal mines (part)

Coal mines	Water inrush time	Depth/ m	Pressure/ MPa	Seriousness	Reasons
Guizhuang coal mine	1993.1.5	−210	2.1~2.5	Flood mine	Collapse column through Ordovician system limestone aquifers
Renlou coal mine	1996.3.4	−335	2.8~3.1	Flood mine	Collapse column through Taiyuan Formation limestone aquifers
Sanhejian coal mine	2002.10.26	−830.1	1.9~2.5	Flood mining area	Fault through Taiyuan Formation limestone aquifers
Dongpang coal mine	2003.4.12	−580	3.1~3.3	Flood mine	Floor failure through Taiyuan Formation limestone aquifers
Xinfeng coal mine	2005.10.19	−200	1.3~1.5	Flood mine	Floor failure through Cambrian system limestone aquifers
Luotuoshan coal mine	2010.3.1	−200	0.3~0.8	31 people died	Collapse column through Taiyuan Formation limestone aquifers
Wangjialing coal mine	2010.3.28	−406	0.4~0.7	38 people died	Floor failure through Cambrian system limestone aquifers
Taoyuan coal mine	2013.2.3	−510.5	0.8~1.2	Flood mine and one person died	Collapse column through Ordovician system limestone aquifers

rock fracturing and fluid flow numerical models which could also help the understanding of the complex phenomenon of water inrush (Shen et al. 2011; Shen et al. 2013). The test model of the mixed water and sand inrush transfer and inrush was designed and manufactured to simulate the mixed water and sand inrush in the overburden fracture channel (Yang et al. 2019). Some protection measures were developed to against water inrush, such as grouting, hydraulic tomography, pillar laying method, filling mining, and so on. (Li et al. 2016; Mao et al. 2018; Sun et al. 2017; Li et al. 2017)

In this study, a new system has been developed to display the development process of floor fractures and the formation of water inrush channels during mining. The results indicated that the floor was in a state of high shear stress which is the zone most prone to water inrush. The trend of the stress change in the floor obtained from the tests was similar to that of the field measurements in Jining mining area located in Shandong province of China. This novel testing system made it possible for experimental investigation on the failure mechanism of mining floors and on the control methods for high pressure water inrush.

Development and components of the test system

In order to show the formation of water inrush channels during coal seam mining, a testing system simulating strata above-confined water was developed. This testing system included a two-dimensional (2D) test bed, a confined water loading system, and a computer-monitoring system as shown in Fig. 1.

2D physical simulation test bed

A grooved guard board (2000 mm (L) × 220 mm (W) × 120 mm (H)) to store the water bag was welded by high-quality carbon structural-steel welding to a grid plate on the test bench. Thread holes that were matched with the 2D test bed guard board were located 25 mm from both ends. An inlet and an outlet were each located 100 mm from both ends in the rear side of the guard plate groove, and a 5-mm-thick support bar was located 15 m from the inner side of the guard board, to support the pressure transfer block.

Confined water loading system

The confined water loading system is consisted of a regulator pump, a water tank, a flexible water bag (floor aquifer), and a strip plate. The polyvinylchloride water bag (1900 mm (L) × 220 mm (W) × 100 mm (H)) could withstand a maximum pressure of 2.0 MPa. The characteristics of polyvinylchloride water bag were flexible and deformable. When the amount of water in the water bag increases, the water bag will bulge. On the contrary, when the amount of water in the water bag decreases, the water bag will collapse. This would change the stress state of the upper strata and better simulate the aquifer. The flexible water bag is divided into six parts by five nozzles as shown in Fig. 2. The caliber of inlet and outlet was 10 mm. The lengths of six parts are 35 cm, 30 cm, 30 cm, 30 cm, 30 cm, and 35 cm, separately. The diameter of nozzle is 5.5 mm. The inlet and outlet were arranged on either sides of the water bag and there are five nozzles on the top of the water bag and two adjacent nozzles are placed 30 cm apart as

Fig. 1 Test system. **a** System
principle diagram. **b** Physical
objects. 1, 2D physical simulation
test bed; 2, confined water
loading system; 2.1, inlet; 2.2,
outlet; 2.3, water switch; 2.4,
regulator pump; 2.5. pressure
gauge; 2.6 storage tank; 2.7,
guard board; 2.8, water bag; 3,
data acquisition system; 3.1, data
line; 3.2, data sampling box

(a) System principle diagram

(b) Physical objects
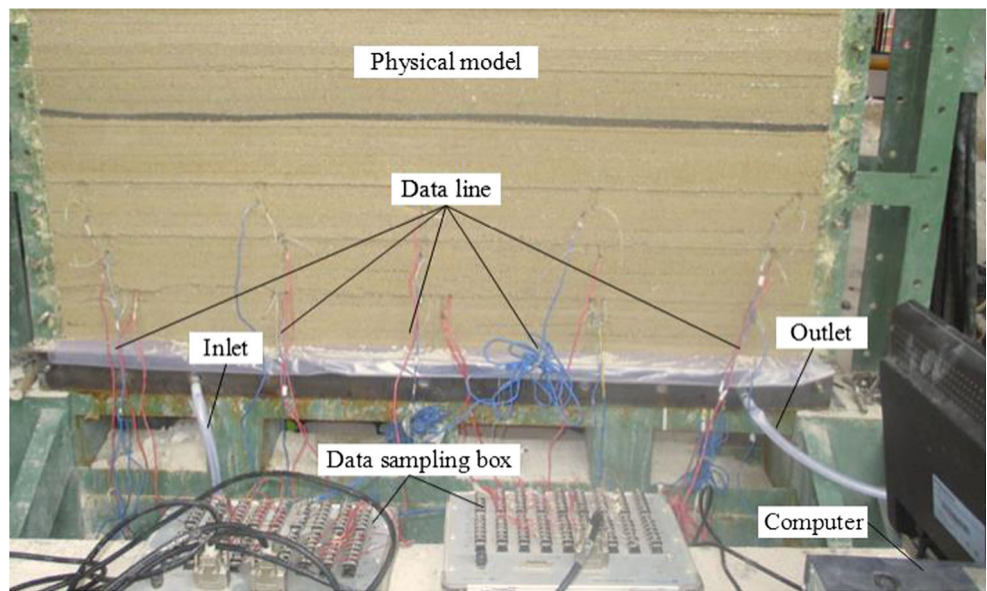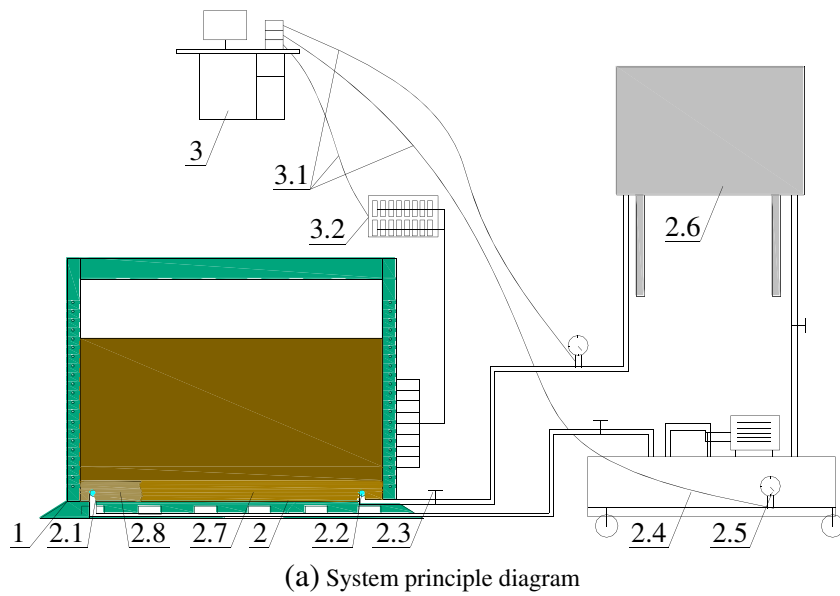
shown in Fig. 2. Tubes, nozzles, and water bag were made of
plastic. They were connected by melting, which ensured that
the interface will not crack under greater pressure. The dis-
tance between adjacent nozzles should be greater than 30 cm,

which not only reduce the number of nozzles and tubes, but
also avoid too much space of model being occupied. A
prefabricated inrush water channel catheter and a nozzle were
located in the middle of the upper section. The water pipe-
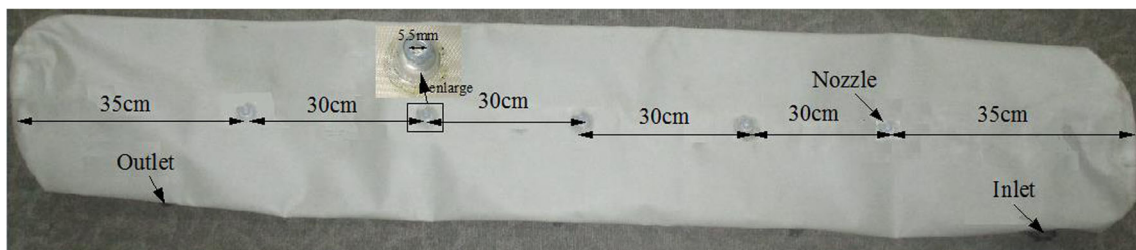
Fig. 2 Flexible water bag

named tube is connected to the nozzle of water bag, and the height of every tube is 32 cm. The diameter of tube and nozzle is the same as 5.5 mm. Hence, the length effect of the water pipe (tube) should be considered, but the diameter effect of it can be ignored due to which is 1/40 of the width of model. The confined water loading system is as shown in Fig. 3.

Data acquisition system

The data acquisition system included water-pressure monitors, pipe flow meters, and floor stress sensors in different monitoring positions as shown in Fig. 4. Based on the water inrush situation, the tube flow meter can monitor water inrush in different layers and analyze the floor rock failure location and the height of progressive intrusion of artesian water. The stress changes in the floor rock strata during mining were monitored using stress sensors.

Physical simulation tests

Model design and paving

The model was designed as shown in Fig. 5, and each layer above the confined water was casted according to the geometric similarity ratio. A uniform load was applied to the upper part of the model and fixed constraints were used in the horizontal direction to simulate the stress state of the surrounding rock. In order to make the fracturing process easy to observe, a large model with the similarity ratio of 1:300 was used. The test model has a dimension of 1900 mm (L) × 220 mm (W) × 1800 mm (H), which is designed to simulate a mining depth of − 800 m. The geological setting of Jining mining area located in Shandong Province of

China has been used to construct the model. The coal column histogram and coal and rock mass mechanical parameters of each layer in the physical simulation model are shown in Fig. 6. The aquiclude plays an important role in water inrush, so its ratio and mechanical property have very important influence on the water inrush in physical model. The floor rocks are composed of sand, $CaCO_3$, Paraffin, and hydraulic oil and the proportion of each component is shown in Fig. 6. The coal seam in the model was 2.0 cm thick, whereas the thickness of floor strata and the overlying strata was 40 cm and 138 cm respectively. Additional loads from upper strata were simulated using a hydraulic loading system which applied a vertical load of 0.032 MPa to the model. The water pressure targeted in the field was 3.0 MPa. Hence, the calculated pressure in the model was 0.01 MPa. This water pressure was supplied automatically by a pressurized water loading system.

The model paving process was as follows: (1) the water bag was placed in the groove with the direction of nozzle upward; (2) the inlet and outlet were connected with steadying pressure pump and storage tank, respectively; (3) those tubes passed through the middle hole of the strip plate and were connected with the nozzle; (4) installed the strip plate with support bars; (5) shut down the outlet and tubes and opened the constant pressure pump;(6) injected a certain amount of water into the water bag until the pressure reached 0.03 MPa; (7) shut down the constant pressure pump and inlet; (8) weighted and mixed the materials required for each layer, inserted these into the model, and laid and compacted them according to the required ratio; (9) laid material mix until the design height was reached and then installed the stress sensors to their design locations; (10) after 4 days, the model had a certain strength and the coal seam was started to be excavated
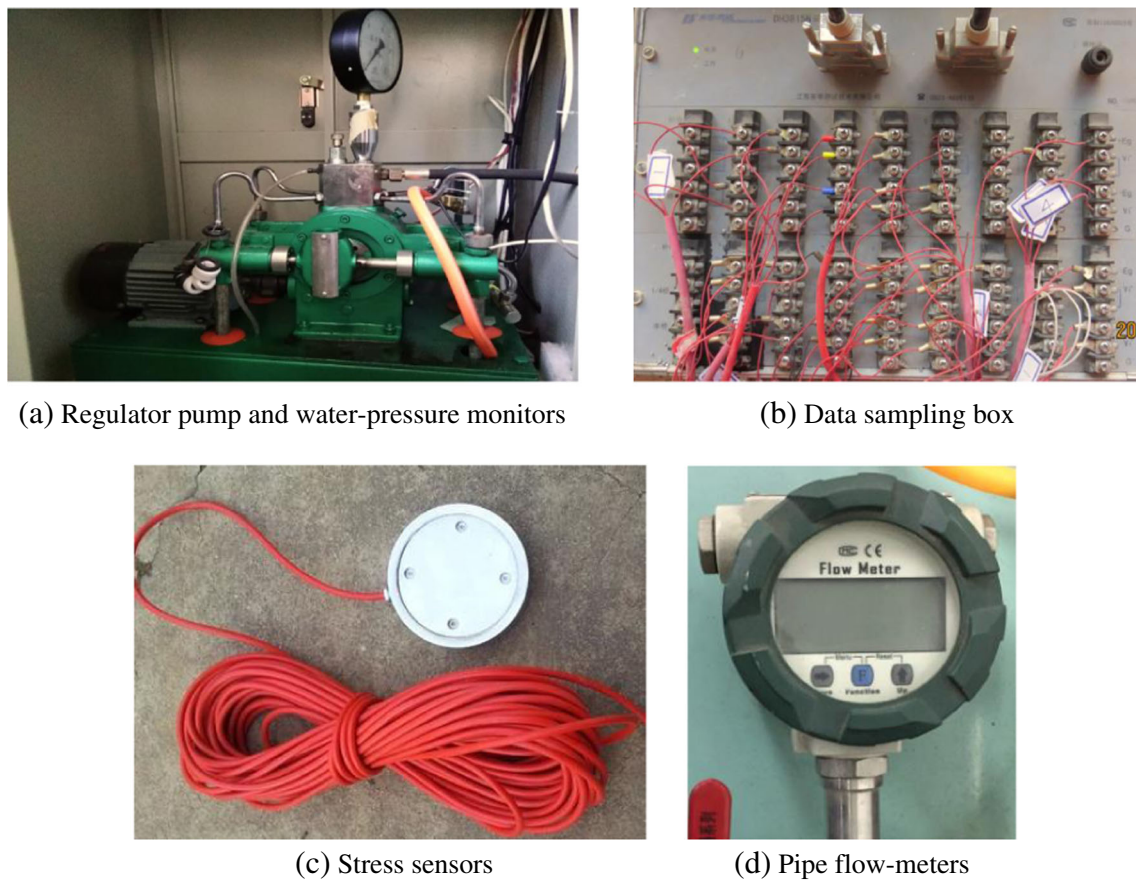

Fig. 3 Confined water loading system

(a) Regulator pump and water-pressure monitors

(b) Data sampling box

(c) Stress sensors
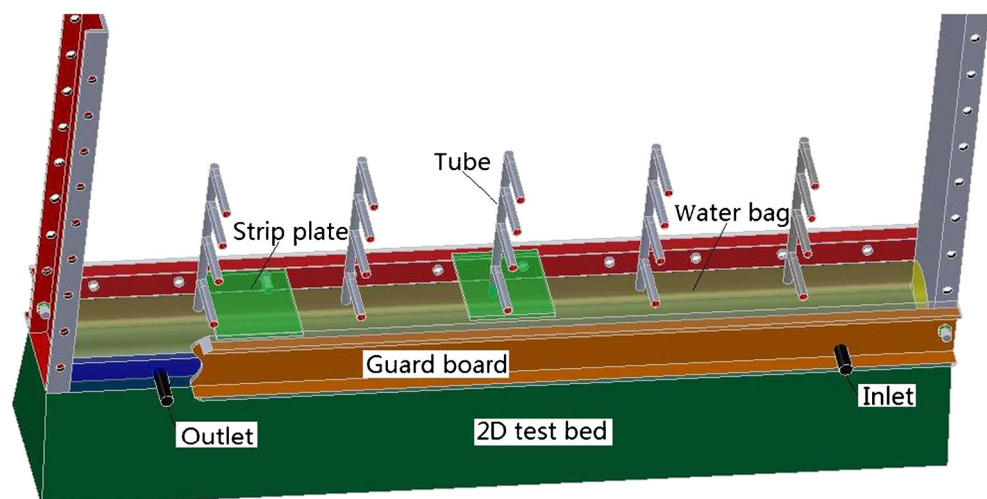
(d) Pipe flow-meters

Fig. 4 Monitoring devices. **a** Regulator pump and water-pressure monitors. **b** Data sampling box. **c** Stress sensors. **d** Pipe flow meters

from the point O (In consideration of the boundary condition effect, the distance between point O and the left boundary of model is 35 cm.). Ten-centimeter seam was left on both sides of the model to reduce the influence of fixed constraints. The point O is shown in Fig. 5; (11) opened constant steadying pressure pump and inlet to maintain the pressure of water bag by continuously adding water. The mechanical and hydraulic response of the floor strata was recorded during the process of excavation.
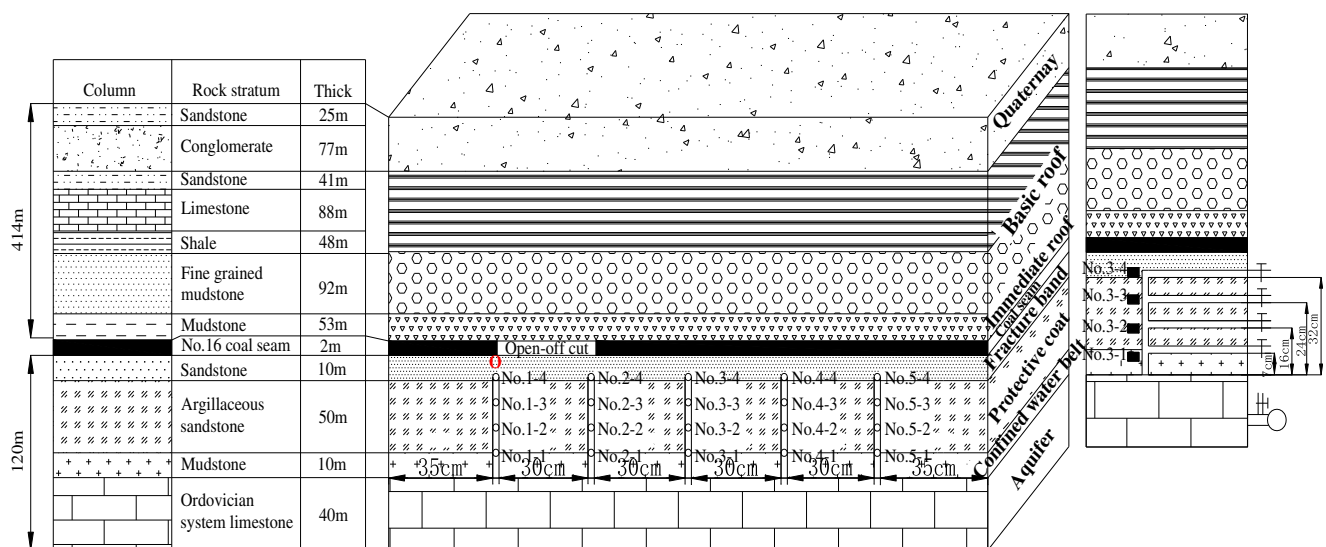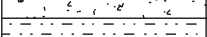

Fig. 5 The model and monitoring points
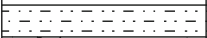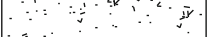
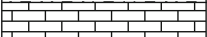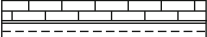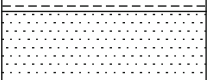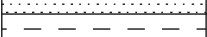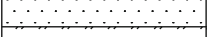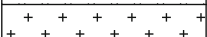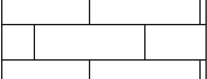| Column	Rock stratum	Thick	Compressive strength of original rock/MPa	Compressive strength of model rock/KPa	Sand:Caco3:Gypsum (Mass ratio)
	Sandstone	25m	7.8	26.0	6:5:5
	Conglomerate	77m	8.2	27.3	7:7:3
	Sandstone	41m	28.4	94.7	7:8:2
	Limestone	88m	38.1	127.0	8:7:3
	Shale	48m	5.8	19.3	6:7:3
	Fine grained mudstone	92m	33.6	112.0	8:5:5
					6:6:4
	Mudstone	53m	4.7	15.3	6:6:4
	No.16 coal seam	2m	2.3	7.6	Sand:Caco3:paraffin :hydraulic oil (Mass ratio)
	Sandstone	10m	29.5	98.3	15:1.2:1.0:0.7
	Argillaceous sandstone	50m	25.0	83.3	15:1.6:0.7:0.7
	Mudstone	10m	4.7	15.3	15:1.2:0.2:0.5
	Ordovician system limestone	40m	9.1	30.0	

Fig. 6 The coal column histogram and coal and rock mass mechanical parameters of each layer. Note: The ratio of 6:5:5 means that the mass ratio of sand to Caco$_3$ and gypsum is 6:1, and the mass ratio of Caco$_3$ to gypsum is 5:5. This ratio rule applies to other rock materials in the roof above coal seam

Test results

When the working face advanced to the maximum self-supporting distance for the roof and floor, the floor rock strata started to fail. This maximum distance for the coal seam excavation was 51 cm, and anew fracture was generated in floor at 10 cm ahead the working face. The fracture is shown in Fig. 7. This fracture was mainly caused by the abutment pressure in front of the working face. As the third group of monitoring points was closest to the crack (Fig. 5), the monitoring data of this group were chosen for analysis. The stress variations with different depths in floor are shown in Fig. 8. When the mining distance increased from 0 to 51 cm. In this experiment, the trends of all stress curve were similar and were consistent with the field observation data from an actual mine (to be discussed later in Fig. 11). The vertical stress

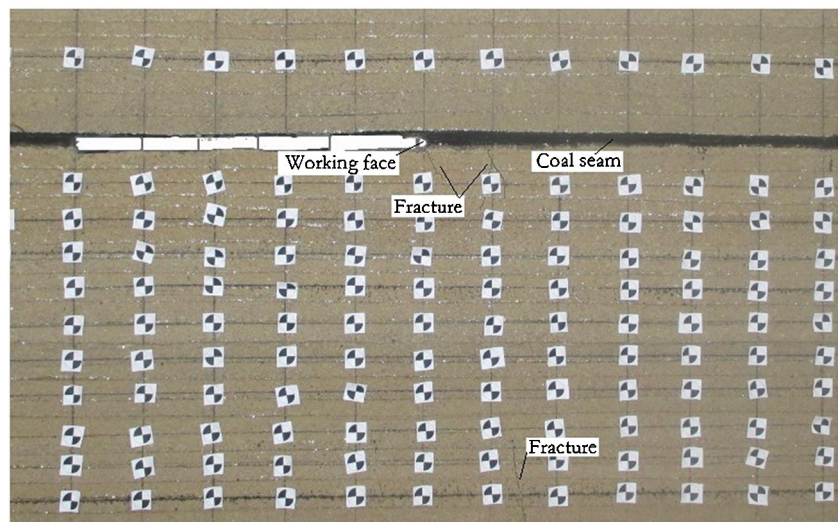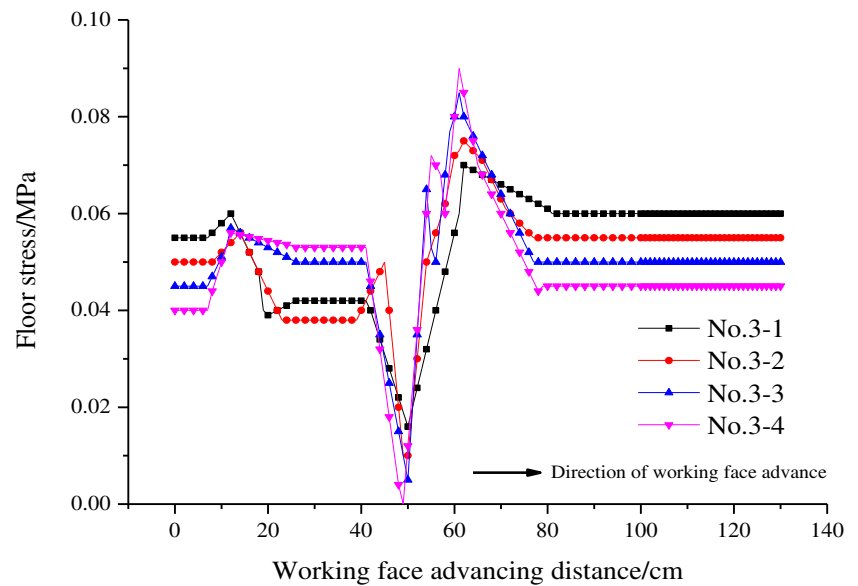**Fig. 7** The fractures produced in floor

increased in the floor in front of the working face and the magnitude of stress at sensors No. 3-1, No. 3-2, No. 3-3, and No. 3-4 were 0.07 MPa, 0.075 MPa, 0.085 MPa, and 0.09 MPa, respectively. When the mining distance increased to 60 cm, the vertical stress reduced rapidly in the floor beneath the working face, with the minimum value of − 0.01 MPa, 0 MPa, 0.003 MPa, and 0.01 MPa, respectively. The fracture length increased with the mining distance and it cut cross through into the floor at the mining distance of 60 cm. At this time, the pressure of the water bag decreased suddenly, and the water inrush channel formed as shown in Fig. 9. Figure 10 showed stress variation at different depths in floor when the mining distance increased to 60 cm. It can be seen that the floor stress is decreasing–rising–falling from the chart in Figs. 8 and 10. This mechanical phenomenon showed

that the floor strata were affected by the pressure of the upper strata and the water pressure of the lower strata. This made the floor strata subjected to compression-shear action and water inrush channel, which can be used to determine the location of water inrush from floor. The experiment results showed that the floor has undergone a process of stress concentration and then distressing. It also visually showed the formation process of the floor water inrush channel, and obtained the law of the floor pressure change before and after the water inrush, which provided important information for blocking the water inrush channel and reducing the water inrush disaster. This cycle of stress change caused the floor fracturing. In this test, the change of strata displacement was not considered. That was because the basic reason for the change of strata displacement was the change of strata pressure. Hence, the change of strata

Fig. 9 Formation of water inrush channel when the mining distance increased to 60 cm
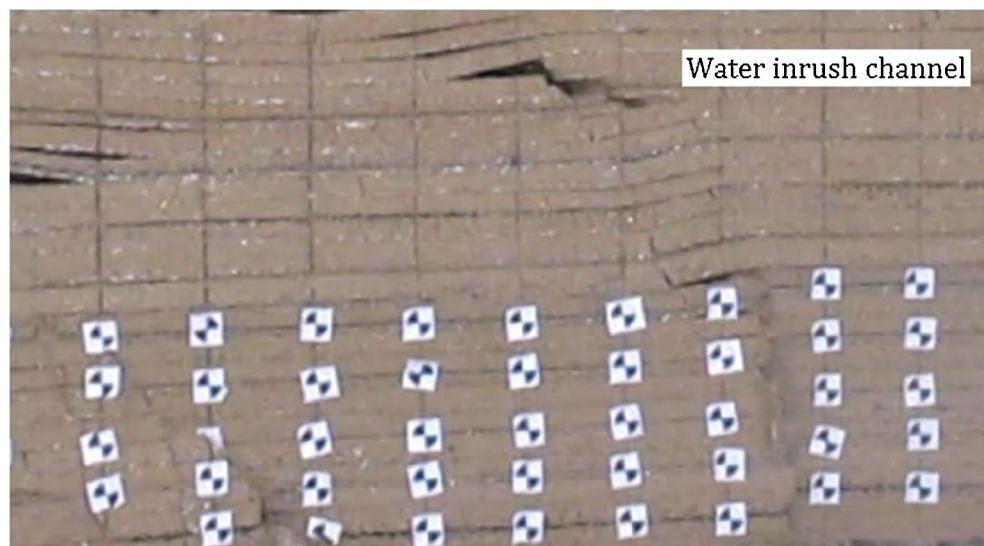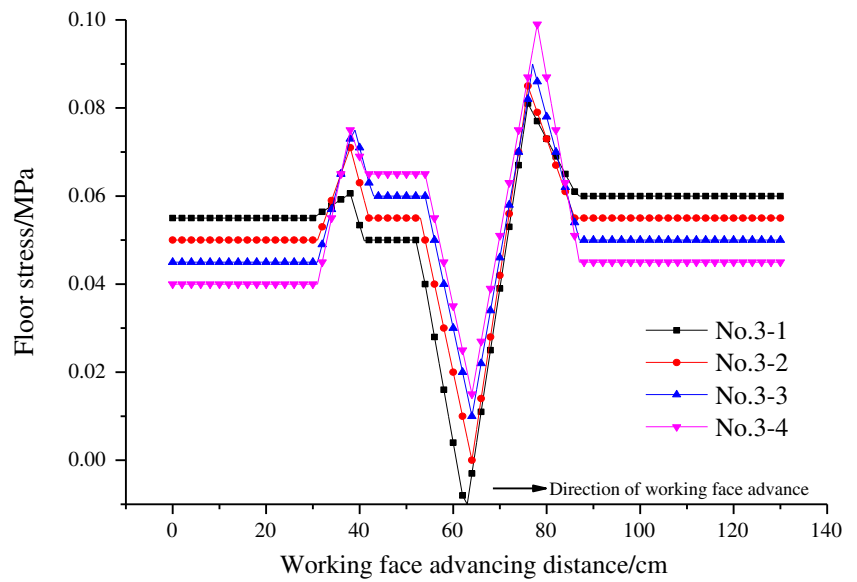
Fig. 10 The variation of vertical stress in floor when the mining distance increased to 60 cm

pressure was prior to the change of strata displacement, and water inrush could be predicted earlier.

Mechanism of flow channel formation in the floor

When a coal seam was mined, a void was then formed to allow the surrounding rock strata to deform. Hence, the surrounding rock moved to the gob and the stress in surrounding rock was redistributed. According to the measurement data of the vertical stress in the floor in Jining mining area in Shandong province of China, floor rock strata can be divided into five zones as shown Fig. 11, namely, stress stable zone, stress recovery zone, stress reduction zone, stress increase zone, and in-situ stress zone. The in situ stress zone was distributed in front of the working face of > 35 m and was mainly caused

by the overburden pressure of overlying strata. After mining of coal seam, the weight of the strata above the gob were redistributed to the coal seam and floor within a distance of 10~35 m in front of working face. A vertical pressure of 1.9~2.0 times higher than that of original stress zone could be produced, forming the stress increase zone. The third zone was stress reduction zone, which was located within a distance of 10 m before and after the working face. The vertical stress in this zone decreased significantly from about 97~102 MPa in the stress increase zone to 15~20 MPa, which was the 1/6~1/5 of the peak value. Stress increase zone and stress reduction zone together made the floor rock into a state of high shear stress due to the sharp vertical stress gradient along the horizontal distance. Therefore, the existing fracture in the floor propagated and new fractures initiated. With the extension of fractures, the confined water in the floor would enter the fracture system and further drive the propagation of the
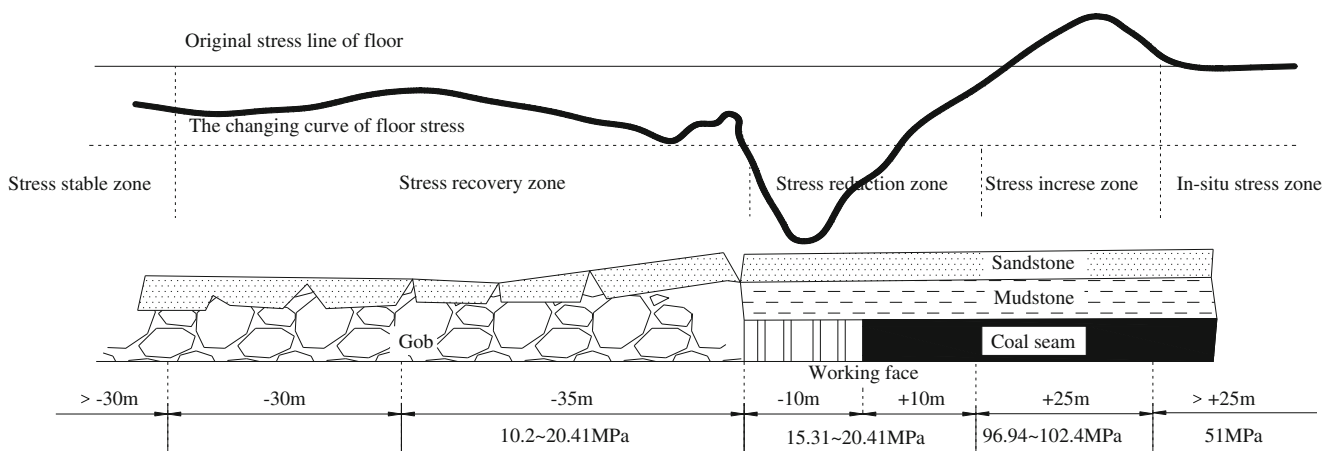

Fig. 11 The variation of floor stress and five zones according to stress observation data

fractures. When the fractures cut through the aquitard layer in the immediate seam floor, water inrush channel was formed quickly. Therefore, the stress reduction zone was usually prone to water inrush. In the stress recovery zone, a part of overlying strata reapplied vertical pressure to the floor and made the cracks to close. The stress value of stress recovery zone was lower than that of in-situ stress zone. Further, behind the stress recovery zone was the stress stable zone which was located about < -65 m from working face. Although the stress of the floor was somewhat restored in this zone, the surrounding rock had been damaged. Hence, the vertical stress value in floor was less than that before mining. The trend was also consistent with the field-monitoring data shown by the black curve in Fig. 11. It could be found that the curves of these three figures have the same trend of change. Figure 11 was a theoretical analysis of Figs. 8 and 10, which reasonably explained the reasons for this trend. The floor rock units experience five zones from "stress stable zone" to "in situ stress zone" with the mining of coal seam. The stress is different in the stress reduction zone and stress increase zone, which cause initiation of shear cracks. The water inrush channels come into being along shear cracks by vertical downward strata pressure and upward water pressure.

Conclusions

According to the above analysis, the main conclusions are presented:

(1) This paper describes a physical simulation model to study water inrush mechanism associated with underground longwall mining. A new testing system simulating strata above confined water was developed, which consisted of three parts: a simulation test bed, a confined water loading system and a computer monitoring system. The pressure of confined water was maintained by using a water bag and by injecting water into it with a constant pressure pump. This system successfully demonstrated the development process of floor fractures and the formation of water inrush channels.

(2) The test results showed that stress increase zone and stress reduction zone occurred in the front and back of working face. These two zones moved forward with the advance of working face. When the distance of the coal seam excavation was 51 cm (or 15.3 m in the field), new fractures initiated in floor of 61 cm (or 18.3 m in the field) below working seam. When the mining distance increased to 60 cm (or 18 m in the field), a through-going fracture was formed and the pressure of the water bag decreased suddenly. The formation of the fracture could be used to predict the occurrence of water inrush disaster.

(3) According to the stress observation data in the floor in Jining mining area in Shandong province of China, the floor rock strata can be divided into five zones. Along the direction of working face advance, they were stress stable zone, stress recovery zone, stress reduction zone, stress increase zone, and in situ stress zone. Stress increase zone and stress reduction zone made the floor in a state of high shear stress due to uneven vertical loading, which together with the high pressure water in the floor aquifer, could cause floor fracturing and consequently water inrush.

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