Simulated Experiment of Water-Sand Inrush across Overlying Strata Fissures Caused by Mining

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In western region of China, the water-sand inrush across overlying strata fissures caused by mining threatens the mine safety production seriously. In order to study the development of water-sand inrush across overlying strata fissures caused by mining, a simulated test system consisted of load support bracket, laboratory module, confined water module, coal seam mining simulator, storage tank, and control system is developed. The combination of coal bearing strata in the south of Shendong mining area is looked on as the engineering background, and a series of new nonhydrophilic composite materials with lower intensity are developed to simulate the coal measure strata. The excavation of physical model can reproduce the whole process of water-sand inrush across overlying strata fissures caused by mining to the life. Under the action of mining and water pressure, after the fourth excavation, the mining-induced vertical fractures of overlying strata pass through the entire bedrock and connect the unconsolidated sand bed, which serves as pathways between the unconsolidated sand bed and working face, triggering water-sand inrush. The water pump suddenly accelerates, and the water yield suddenly increases to the extreme value of 150 L/h. The water pressure rapidly drops to 0 MPa, and a small amount of colored sand enters into the fractures of overlying strata and flows out with the water. The distribution of support pressure around the working face can be divided into 4 areas obviously, that is, the original stress area, the stress-concentrated area, the stress-released area, and the stress restoration area. Test results show that the system is stable and reliable, which have important significance for studying the formation mechanism of water-sand inrush across overlying strata fissures further.

1. Introduction

In western region of China, the thickness of coal seam is larger, the buried depth is shallower, the bedrock is thinner, and there is also a thick unconsolidated sand bed near the surface [1–4]. The mining of such coal seam can lead to intense overlying strata movement and impact wider range. The overlying strata are difficult to form a stable structure. The fractures of overlying strata are fully developed, which can even reach the surface and form larger ground fissures and sidestepped subsidence [5, 6]. If the water of the thick unconsolidated sand bed near the surface is good, the mixture of water-sand will inrush the coal working face across overlying strata fissures, which may lead to property losses and even casualties, and seriously threaten the mine safety production [7–15]. In order to get rid of the serious problems of water-sand inrush across overlying strata fissures during coal resource development, studies about deformation and failure of overlying strata, development and propagation of fractures, and seepage and inrush of water-sand are badly needed, which are the basis of researching the mechanism of water-sand inrush across overlying strata fissures [16–20]. The mechanism and influencing factor of water-sand inrush across overlying strata fissures are difficult to obtain by field observation because of the concealment of underground excavation engineering; laboratory tests become an effective way of solving this problem [21–24]. Some scholars have designed or optimized the relevant test equipment and carried out the simulated test research.

Liang et al. [25] and Tang et al. [26] designed a sealed container equipped with pressure and measuring devices, which was 0.8 m high and 1.8 m in diameter. The process of
water-sand inrush was simulated, and influencing factors of
water-sand inrush were determined initially. Sui et al. [27,
28] refitted the TST-70 permeameter. The overlying strata
deforestation and failure types and mechanisms caused by
permeation in caving zone and fracture zone were simulated;
the aperture of fracture and initial water pressure of water-
bearing stratum were the key factors influencing water-sand
inrush in underground mining face. Yang et al. [29, 30]
designed an experimental facility for simulating the migration
characteristics and inrush mechanism of water-sand
mixture, which included an experiment tank and an experi-
ment barrel.

Although these previous studies have provided a good
understanding of the mechanism and influencing factor of
water-sand inrush across overlying strata fissures, the exist-
ing test systems still have some deficiencies. (1) The existing
test systems cannot reproduce the whole process of water-
sand inrush across overlying strata fissures caused by mining
to the life, which can only reproduce the happening process
of water-sand inrush. (2) The structure, shape, and size of
water-sand inrush channels are set artificially, which are not
formed under the influence of mining and water pres-
sure. (3) During the working face mining, the deformation
and failure of overlying strata, fissure extension of overlying
strata, and formation of water-sand channels cannot be
observed directly. (4) After the working face mining, the spa-
tial structure form of overlying strata and the distribu-
tion form sand and water channel cannot be exposed
directly. In order to overcome the deficiencies of existing
test systems, the simulated test system for water-sand
inrush across overlying strata fissures caused by mining is
developed. The coal measure strata in the western region
of China are looked on as the engineering background,
and the new nonhydrophilic composite materials with lower intensity are developed to simulate the coal measure
strata. The excavation of model can reproduce the whole
process of water-sand inrush across overlying strata fissures
caused by mining to the life.

2. Test System Structure

The simulated test system for water-sand inrush across over-
lying strata fissures caused by mining consisted of load sup-
port bracket, laboratory module, confined water module,
coil seam mining simulator, storage tank, servo control
system of water pressure and water yield, and servo control
system of displacement and stress, as shown in Figure 1.

2.1. Load Support Bracket. The load support bracket
consisted of base, frame, supporting structure of hydraulic
cylinder, and reaction frame, as shown in Figure 1. Two legs
are fixed on the base. Two hydraulic cylinders are fixed on the
top beam, which is supported firmly by the two legs. Two
squeeze heads for providing lateral restriction are installed
on the inside of the legs. Two deformation resistant sup-
ports are installed between the leg and the beam for
enhancing the bearing capacity and deformation resistant
capacity of the frame.

2.2. Laboratory Module. The structure of laboratory module
is shown in Figure 2. The effective sizes of length, width,
and height are 1200 mm, 400 mm, and 700 mm, respectively.
In order to observe the deformation and failure of overlying
strata, fissure extension of overlying strata, and formation
of water-sand channels directly, a piece of complete organic
glass plate with high strength and good transparency is
selected as the front baffle plate. Two deformation resistant
beams are configured to reduce the deformation of the front
baffle plate and enhance the airproof of the laboratory cham-
ber. A piece of complete corrosion resistant plate with 20 mm
thickness is selected as the back baffle plate that enhances
the deformation resistant capacity of the laboratory chamber.
The junction surfaces between baffle plates and vertical plates
are sealed by rubber sealing strips, which are installed in the
installation channels. A water-sand collecting tank is located
on the bottom of laboratory module.

2.3. Confined Water Module. Confined water module can
supply water to the laboratory module, which is connected
by connecting pieces with hydraulic cylinders. At the bottom
of the confined water module, 32 drainage holes with 4 mm
diameter are equally distributed. In order to improve the
sealing performance of the laboratory module, an installation
channel with 5 mm depth and 15 mm width is reserved for
installing the seal ring. Confined water module can also be
used as the load head, which can provide vertical load to
the laboratory model.

2.4. Coal Seam Mining Simulator. The manual excavation is
the common method for excavating the traditional similar
material model, which has the following drawbacks: (1) the
process of excavation is difficult to maintain a constant exca-
vation step distance and speed. (2) It is difficult to achieve 3D simulation of coal mining. (3) In the process of excavation,
the caving roof will fall into the operating space and impact
the excavation of similar material model. (4) It is necessary
to remove the baffle plates of laboratory module for the exca-
vation of similar material model, which reduces the plugging
ability of laboratory module.

Considering the above drawbacks, a coal seam mining
simulator is designed, which consists of 3 parts: (1) 13 stain-
less steel plates, which is used to simulate the coal seam, the
specific size and arrangement are shown in Figure 3(a). The
size of steel plate can be changed with the change of geologic
and mining condition and ratio of similitude of the physical
model. (2) 7 rollers, the purposes are to support upper load
and reduce the frictional drag in the process of drawing the
steel plate from the physical model, as shown in Figure 3(a). (3) Drawing device, which is connected with
the steel plates by connecting pieces, is shown in
Figure 3(b). By turning the handle at a constant speed, the
steel plate will be pulled from the physical model to simulate
the mining of coal seam.

2.5. Storage Tank. In order to guarantee the stability of water
pressure and water yield, the storage tank is designed, as
shown in Figure 4. The storage tank is cylindrical; the thickness
and internal diameter and height are 10 mm, 300 mm, and
1000 mm, respectively. The flowmeter and water pressure sensor are installed in the water outlet of storage tank, which are located in the back of storage tank.

2.6. Control System. The control system consists of console and servo loading system, as shown in Figure 5. The servo loading system consists of servo control system of water pressure and water yield and servo control system of displacement and stress. (1) Console is fully automated; five basic parameters can be collected into a database in real time, such as time, displacement, loading, water pressure, and water yield. The maximum sampling frequency is 10 HZ. (2) Servo control system of water pressure and water yield can fill the testing chamber with water by setting water pressure or water yield. The maximum water pressure is 2 MPa, the maximum water supply is 150 L/h, and the accuracy is 0.01 MPa. (3) Servo control system of displacement and loading can control the loading head by setting displacement or loading. The meter full scale of displacement is 400 mm, and the accuracy is 0.01 mm. The maximum loading is 1000 KN, and the accuracy is 0.01 KN.

3. Experimental Scheme of Physical Simulation

3.1. Engineering Background. Shendong mining area is located in western region of China, which is one of the largest
Steel plates for simulating coal seam
Installation channel of transmission line
Back baffle plate of laboratory module
Rollers
Supports of rollers
(a) Stainless steel plates and rollers

Organic glass plate
Connecting piece
Drawing device
(b) Drawing device

Figure 3: Coal seam mining simulator.

Air outlet
Tank
Support
Water inlet
Flowmeter
Water outlet
Water pressure sensor
Tank

Figure 4: Storage tank.
coal mining area in China [31–33]. In the south of Shendong mining area, the thickness of coal seam is larger, the buried depth is shallower, the bedrock is thinner, and there is also a thick unconsolidated sand bed near the surface. The combination of coal bearing strata is shown in Figure 6.

(1) The Quaternary is mainly consists of Holocene and Salawusu Formation (belonging to Upper Pleistocene); the average thickness of it is 15-50 m. Holocene consists of aeolian sand, loess, and sand and gravel. The average thickness of aeolian sand aquifer
Table 1: Similar material ratio of different strata.

| Number of stratum | Lithology         | Real rock stratum | Similar material | Material ratio (sand: paraffin: Vaseline: hydraulic oil: lime carbonate) |
|------------------|-------------------|-------------------|------------------|-------------------------------------------------------------------------|
|                  |                   | Thickness/m       | Thickness/m      |                                                                          |
| 10               | Aeolian sand      | 50                | 0.20             | –                                                                       |
| 9                | Mudstone          | 10                | 0.04             | 50.1                                                                     | 40 : 0.4 : 1 : 1 : 3 |
| 8                | Fine sandstone    | 10                | 0.04             | 59.7                                                                     | 40 : 0.43 : 1 : 1 : 3 |
| 7                | Medium sandstone  | 7.5               | 0.03             | 85.9                                                                     | 40 : 0.5 : 1 : 1 : 3 |
| 6                | Arenaceous mudstone| 5                | 0.02             | 97.9                                                                     | 40 : 0.54 : 1 : 1 : 3 |
| 5                | Fine sandstone    | 7.5               | 0.03             | 125.1                                                                    | 40 : 0.62 : 1 : 1 : 3 |
| 4                | Mudstone          | 5                 | 0.02             | 80.3                                                                     | 40 : 0.5 : 1 : 1 : 3 |
| 3                | Medium sandstone  | 7.5               | 0.03             | 108.0                                                                    | 40 : 0.6 : 1 : 1 : 3 |
| 2                | Fine siltstone    | 10                | 0.04             | 95.2                                                                     | 40 : 0.53 : 1 : 1 : 3 |
| 1                | Mudstone          | 5                 | 0.02             | 70.7                                                                     | 40 : 0.46 : 1 : 1 : 3 |
| 0                | Coal seam         | 7.5               | 0.03             | –                                                                        | Steel plates for simulating the coal seam |

Figure 7: Effect of paraffin content to the parameters of similar material.

Figure 8: Physical model laying.

Figure 9: Layout of stress sensors.

Figure 10: Unexcavated similar material model.
is about 3 m, the depth of ground water level is 0-5 m, the osmotic coefficient is 0.061 m/d, and specific yield is 0.0188 L/(s·m), so the water yield property of aquifer is weak. Salawusu Formation is mainly fluviatile and lacustrine sediment, the upper of Salawusu Formation consists of fine sand and silt, the middle of Salawusu Formation is medium sand and coarse sand, and the lower of Salawusu Formation is sand and gravel. The thickness of Salawusu Formation aquifer is 10-30 m, the osmotic coefficient is 0.88-

Figure 11: Deformation and failure of overlying strata.
3.4. Production of Physical Model. Before laying the physical model, steel plates for simulating the coal seam should be reset firstly, and the signal transmission lines of stress sensors should be imported into the laboratory module through the installation channel of transmission line. The physical model is laid layer by layer. According to the similar material ratio of different strata, the required mass of each component can be calculated exactly. The sand and lime carbonate are stirred uniformly and heated to about 80°C with the wok. The paraffin, Vaseline, and hydraulic oil are heated to about 60°C with water bath kettle until they become liquid completely. Then, they are mixed quickly, poured into the laboratory module, and processed into the similar stratum, as shown in Figure 8. The mica powder is used between adjacent strata as the boundary. Eight stress sensors are buried above the coal seam in the physical model for monitoring the support pressure change of overlying strata caused by mining, as shown in Figure 9. The unexcavated similar material model is shown in Figure 10.

3.5. Steps of Physical Model Excavation. The steps of water-sand inrush simulated experiment are as follows: (1) starting the servo control system of displacement and stress, using displacement control mode to adjust the gap between the load head and test materials until the gap is about 100 mm; (2) starting the servo control system of water pressure and water yield, using water pressure control mode to keep the water pressure in the laboratory module at 0.1 MPa; and (3) taking two minutes to pull the steel plate for simulating the coal seam from the physical model at a constant speed, the time interval of adjacent steel plate is one hour. During the working face mining, the deformation and failure of overlying strata, fissure extension of overlying strata, and the formation of water-sand channels could be observed directly through the organic glass plate. The support pressure change of overlying strata caused by mining could be monitored by stress sensors in real time. The water pressure and water yield could also be monitored by water pressure sensor and flowmeter in real time.
4. Experimental Results of Physical Simulation

4.1. Analysis of the Overlying Strata Deformation and Failure. After the first excavation, only the immediate roof presents slight bed separation, and there is no fissure, as shown in Figure 11(a). During the second excavation, the bed separation space between adjacent stratum becomes larger gradually, and the immediate roof breaks and falls into the gob. As time goes on, multiple strata above the immediate roof present bed separation, as shown in Figure 11(b). During the third excavation, because the span of some overlying strata exceeds the limit, the curved strata cannot bear their own weight, break into blocks, and fall into the gob; the caved zone extends to No.4 stratum (mudstone), but the mining-induced fractures of overlying strata above the caved zone are not obvious, as shown in Figure 11(c).

During the fourth excavation, the height of caved zone becomes higher, and the mining-induced fractures of overlying strata above the caved zone become obvious and extend to the bottom of the unconsolidated sand bed gradually, which serves as pathways between the unconsolidated sand bed and working face, triggering water-sand inrush, as shown in Figure 11(d). During the subsequent excavation, the opening of mining-induced vertical fractures decreases gradually and even disappears, as shown in Figures 11(e)–11(g).

4.2. Regularity of Support Pressure Distribution. Throughout the working face mining, the pressure changes monitored by No.2 stress sensor are shown in Figure 12. During the first and second excavation, No.2 stress sensor is located in front of the working face; the data monitored by it reflect the advance support pressure, which is greater than the original stress. During the third excavation, No.2 stress sensor is just located above the working face; the data monitored by it display the tendency of increasing first and then decreasing sharply and increasing slowly again. During the subsequent excavation, No.2 stress sensor is located behind the working face; the data monitored by it display the tendency of increasing slowly, which are infinitely close to the original stress. The distribution of support pressure around the working face can be divided into 4 areas, that is, the original stress area, the stress-concentrated area, the stress-released area, and the stress restoration area, as shown in Figure 13.

4.3. Relationship between Water Pressure, Water Yield, and Water-Sand Inrush. Before the mining-induced vertical fractures of overlying strata pass through the entire bedrock and connect the unconsolidated sand bed, the water pressure in the laboratory module can maintain a dynamic constant of 0.1 MPa, but a certain amount of water yield occurs. The water seepage becomes more and more obvious with the working surface mining. After the fourth excavation, the mining-induced vertical fractures of overlying strata connect the unconsolidated sand bed, which serves as pathways between the unconsolidated sand bed and working face, triggering water-sand inrush. The water pump suddenly accelerates, and the water yield suddenly increases to the extreme value of 150 L/h. The water pressure rapidly drops to 0 MPa, and a small amount of colored sand enters into the fractures of overlying strata and flows out with the water. The changes of water pressure and water yield are shown in Figure 14.

5. Conclusions

(1) In western region of China, the water-sand inrush across overlying strata fissures caused by mining threatens the mine safety production seriously. In order to study the development of water-sand inrush across overlying strata fissures caused by mining, a simulated test system consisted of load support bracket, laboratory module, confined water module, coal seam mining simulator, storage tank, and control system is developed.
(2) The combination of coal bearing strata in the south of Shandong mining area is looked on as the engineering background, and a series of new nonhydrophilic composite materials with lower intensity are developed to simulate the coal measure strata.

(3) The excavation of physical model can reproduce the whole process of water-sand inrush across overlying strata fissures caused by mining to the life. Under the action of mining and water pressure, after the fourth excavation, the mining-induced vertical fractures of overlying strata pass through the entire bedrock and connect the unconsolidated sand bed, which serves as pathways between the unconsolidated sand bed and working face, triggering water-sand inrush. The water pump suddenly accelerates, and the water yield suddenly increases to the extreme value of 150 L/h. The water pressure rapidly drops to 0 MPa, and a small amount of colored sand enters into the fractures of overlying strata and flows out with the water. The distribution of support pressure around the working face can be divided into 4 areas obviously, that is, the original stress area, the stress-concentrated area, the stress-released area, and the stress restoration area.

(4) Test results show that the system is stable and reliable, which have important significance for studying the formation mechanism of water-sand inrush across overlying strata fissures further.

Data Availability
The data used to support the findings of this study are included within the article.

Conflicts of Interest
The authors declare no conflicts of interest.

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