Research Article

Physical Modeling of the Controlled Water-Flowing Fracture Development during Short-Wall Block Backfill Mining

Yun Zhang¹,², Yongzi Liu¹,², Xingping Lai¹,² and Jianming Gao¹,²

¹School of Energy Science and Engineering, Xi’an University of Science & Technology, Xi’an, Shaanxi 710054, China
²Key Laboratory of Western Mines and Hazard Prevention of Ministry of Education, Xi’an University of Science & Technology, Xi’an, Shaanxi 710054, China

Correspondence should be addressed to Yun Zhang; zhangyun@xust.edu.cn

Received 11 September 2021; Accepted 15 November 2021; Published 1 December 2021

Academic Editor: Yonghui Wu

Copyright © 2021 Yun Zhang et al. Exclusive Licensee GeoScienceWorld. Distributed under a Creative Commons Attribution License (CC BY 4.0).

Short-wall block backfill mining (SBBM) technology is an effective method to solve the environmental problems in the mining process. Based on the technical characteristics of SBBM technology and the physical similarity criterion, the physical similarity models for comparing the control effects of water-flowing fracture (WFF) development using short-wall block cave mining (SBCM) and SBBM were established, and the deformation and the WFF development of overlying strata above gob were monitored. The test results determined that the composite materials of 5 mm thick pearl sponge + 5 mm thick sponge + 10 mm thick paper + 6 mm thick board were adopted as the similar backfill materials by comparing the stress-strain curves between the similar backfill materials and the original gangue sample. When the backfilling body was filled into the gob, it would be the permanent bearing body, which bore the load of the overlying strata accompanied with the protective coal pillar. At the same time, the backfilling body also filled the collapse space of overlying strata, which was equivalent to reduce the mining height, and effectively reduced the subsidence and failure height of the overlying strata. Compared with SBCM, the test results showed that the maximum vertical deformation, the height of water-flowing fractured zone, and activity range of overlying strata using SBBM were reduced by 91.4%, 82.5%, and 64.9%, respectively. SBBM had a significant control effect on strata damage and WFF development, which could realize the purpose of water resource protection in coal mines.

1. Introduction

Due to the influence of geological conditions of the coal mine and layout of the long-wall mining working face, the reserves of coal resources under buildings, railways, and water bodies are increasing day by day. Recovering coal resources under aquifer is one of the effective means to promote the stable and sustainable development of the coal mines [1–3]. However, when the caving mining method is adopted, obvious movement and deformation of the overlying strata will occur after coal mining [4], which will inevitably cause rock collapse and fracture, resulting in the formation of WFF [5–7]. Once the aquifer is close to coal seam, WFF can easily develop to aquifer or surface water area, which will cause a large loss of water resource and may further induce series environmental problems [8–10]. In addition, with the high-intensity and large-scale coal mining, a large amount of gangue will be discharged and accumulated to the surface in the mining process, which brings a severe threat to the ecological environment of the mining area [11]. Figure 1 shows the environment issues were caused by coal mining. The waste of coal resource and the destruction of the ecological environment of the coal mines are great challenges to the government’s sustainable development strategy [12, 13]. In this paper, the SBBM method was proposed to recover the coal seam under aquifer, which could not only solve the problem of environmental pollution caused by the accumulation of gangue on the surface but also realize the positive control of the WFF development, so as to provide an effective mining method solving the problems of water resource loss and gangue surface accumulation caused by coal mining.
Currently, theoretical research on the development law of WFF and the protection of water resource in the mining area had been intensively investigated. Xu et al. [14, 15] studied the relationship between the location of key stratum and the development law of WFF and proposed a novel method for the estimation of height of water-flowing fractured zone. Miao et al. [16] introduced the concept of water-resistant key stratum and analyzed the basic distribution characteristics of through fracture in water-resistant key stratum. Fan et al. [17, 18] proposed the method of locally preserving water-proof pillar to control of the WFF development and summarized the problems existing in the water-preserved mining research in the western China. For solid backfill mining with gangue, Zhang et al. [19, 20] proposed the equivalent mining height model based on the study of mechanical properties of gangue backfill materials. Yan et al. [21] analyzed the deformation and failure characteristics of the shaft under the caving mining and backfill mining by physical similarity simulation test and revealed the control mechanism of shaft deformation of backfill mining with gangue. Based on the compaction characteristics of gangue materials from the perspective of strata control, Huang et al. [22, 23] proposed the design method of backfill ratio of working face. However, the research on the control of WFF development under the aquifer using SBBM had rarely been investigated, and further researches and explorations were urgently needed.

In this study, an experimental coal mine in Yan’an, Shaanxi Province, was taken as the engineering background; based on the characteristics of SBBM technology, a physical similarity simulation test was adopted to analyze the control effect of WFF development under the aquifer using SBBM. The deformation and characteristics of WFF development in overlying strata using SBCM and SBBM were compared; the control mechanism of WFF development using SBBM was revealed. Moreover, the prevention system of water resource loss was proposed. The present study exhibits important engineering and reference significance for further prolonging the service life of coal mines, ecological environment protection, and reasonable recovery of coal seams under aquifer.

2. SBBM Technology and Engineering Background

2.1. SBBM Technology and Key Equipment of Working Face. SBBM was mainly used to recover coal resources, such as coal resources under buildings, railways, water bodies, and marginal coal pillars. SBBM was designed on the basis of technology and production system of SBCM. In the process of SBBM, after a block had been mined, the gangue materials were filled into the gob while the next block was mining, thus ensuring that the mining process and the backfilling process were carried out simultaneously, and realized the effective backfill mining method of "simultaneous mining and backfilling." The application of SBBM technology could recover coal seams under aquifer, which would improve the recovery ratio of coal resource and reduce the cost of coal production. Furthermore, gangue materials were backfilled into the gob, which reduced the damage to the ecological environment (the problems of water resource loss and gangue accumulation) and minimized the cost of geoenvironmental restoration protection of coal mines. It effectively took into account the economic and environmental benefits of coal mines and provided an effective method for realizing the green mining mode in the western China.

The SBBM working face was divided into several blocks according to the size of the mining area; protective coal pillars with certain widths were set between the adjacent blocks. Each block was divided into multiple recoveries of coal pillars to be mined by arranging branch roadways and connected roadways. In the process of recovering the recovery of coal pillars, the recovery sequence was mining in retreat. The width of each wing was about 3 m, the length of each wing was generally less than 11 m, and the width range of temporary coal pillar between wings was about 0.5–1.5 m. Once a block was fully mined, a seal dam was built at the connected roadway; then gangue materials as backfilling body were filled into the wings, branch roadways, and connected roadways in time. The backfilling sequence was consistent with the recovery sequence. The coal pillars and seal dams played the role of baffles and ensured that the backfilled gangue materials could be connected with the roof.

Figure 1: Environment damages were caused by coal mining in China. (a) Accumulation of gangue on the surface. (b) Fractures reach to surface. (c) Reduced surface vegetation.
The SBBM technology mainly included mining technology and backfilling technology. The mining technology of working face was as follows: firstly, the continuous miner was used to complete the mining process of branch roadways and connected roadways. In the process of recovering the recovery of coal pillars, four crawler walking hydraulic supports were used to cooperate with the continuous miner, two of them were arranged in the branch roadway in the mining working face, and the other two were arranged in the connected roadway which was closest to the mining working face. The backfilling technology of working face was as follows: after the recovery of coal pillars, a seal dam was arranged in the connected roadway, so as to provide an effective guarantee for the safe and high-quality completion of the subsequent backfilling process. At the same time, two crawler hydraulic supports were arranged in the branch roadway, and the transported gangue materials were thrown into the branch roadway and wings by a conveyor and gangue throwing machine. When the backfilled gangue materials accumulated to a certain height, the loose backfilled gangue materials were pushed by a bulldozer, the backfilling materials were required to be connected to the roof. The SBBM working face layout and equipment are shown in Figure 2.

2.2. Engineering Background. The experimental coal mine was located in the south of Yan’an City, Shaanxi Province, with the coal mine field area of about 197.5 km² and the comprehensive approved production capacity of 4.2 million t/a. At present, the minable coal seam of the coal mine was #2 coal seam, of which the structure was simple and stable with no fault, the thickness variation of #2 coal seam was small, and the average dip angle was about 2.0°; it belonged to typical shallow flat seam in the western China, with an average buried depth of about 141.6 m and an average thickness of about 4.0 m. The main protective water resource in the experimental coal mine was surface water, which was located above the loess layer. Due to the shallow buried depth of the coal seam, the height of the water-flowing fractured zone was relatively large by coal mining; it was necessary to avoid the damage of water resource caused by coal mining.

The experimental SBBM working face was located in the east of 406 long-wall working face, with a mining area of about 25300 m². It was estimated that the total recoverable coal amount was 145000 t and the increased benefit was about 87 million. According to the S81 borehole near the experimental SBBM working face, the roof above #2 coal seam in the experimental mining area consisted of 2.0 m thick mudstone, 12.8 m thick siltstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, 12.8 m thick mudstone, and 34.2 m thick loess layer from bottom to top. In order to protect the surface water resource, in view of the geological conditions of #2 coal seam and maximizing the disposal gangue, the coal mine planned to recover the experimental mining area by three blocks, with a design mining height of 4.0 m, a block length of 70 m, a protective coal pillar width of 10 m, and a working face backfill ratio of 80%, thus preventing the WFF to reach to the surface, resulting in the loss of water resources. The location of experimental coal mine and the geologic columns are shown in Figure 3.
3. Physical Similar Simulation Test of Control Effect of WFF Development Using SBBM

In order to study the control effect of WFF development using SBBM, a physical similar simulation test was carried out in this paper; the deformation characteristics and development law of WFF in overlying strata using SBCM and SBBM were studied. Given the geological condition of the experimental coal mine as the engineering background, the two-dimensional plane model with a size of 2.5 m × 0.2 m × 1.6 m was paved by sand, calcium carbonate, gypsum, water, and other evenly mixed materials. The model included 13 layers from #2 coal seam floor to the surface. Two groups of comparative tests were designed: scheme 1 was SBCM; scheme 2 was SBBM, and its backfill ratio of working face was set to 80%. According to the physical similarity criterion and geological structure of experimental SBBM working face [24, 25], it was calculated that the following conditions should be satisfied between the physical similarity model and the prototype: the similarity ratio of bulk density was 1 : 1.667, the geometric similarity ratio was 1 : 150, and the similarity ratio of stress and strength was 1 : 250. According to the calculation, the proportion of each materials is shown in Table 1. Materials were mixed evenly according to the mass (Table 1) and then laid evenly on the model frame from bottom to top and tamped the materials with a special hammer to the design layer height.

The mica sheets with a thickness of no more than 1 mm were laid between two adjacent layers.

In the process of physical similar simulation test, because the selected the sand contained a certain amount of water and if the water content of sand was not considered, the accuracy of the physical similar simulation test would be influenced. Therefore, six river sand samples with a weight of 250 g were selected before laying the model, and they were dehydrated in drying closet; Figure 4 shows the weights of sand samples before and after dehydration. Then, the average water content was calculated by Equation (1), and the value was 4.65%.

\[ a = \frac{m_b - m_a}{m_b}, \]

where \( a \) is the water content of sand, \( m_b \) is the weight of sand before dehydration, and \( m_a \) is the weight of sand after dehydration.

Substitute the water content of sand (4.65%) into Equation (2) to adjust the actual weight of sand in the model.

\[ m'_b = \frac{m_b}{1 - a}, \]

where \( m'_b \) is the adjusted weight of hydrous sand required after model correction and \( m_b \) is the weight of dry sand required before model correction.

---

| NO. | Columnar | Thickness/m | Lithology    |
|-----|----------|-------------|--------------|
|     |          | Total       | Layer        |
| 1   |          | 34.2        | 34.2         |
| 2   |          | 45.2        | 11.0         |
| 3   |          | 76.5        | 31.3         |
| 4   |          | 80.0        | 3.5          |
| 5   |          | 85.0        | 5.0          |
| 6   |          | 99.2        | 14.2         |
| 7   |          | 116.1       | 16.9         |
| 8   |          | 121.0       | 4.9          |
| 9   |          | 126.8       | 5.8          |
| 10  |          | 139.6       | 12.8         |
| 11  |          | 141.6       | 2.0          |
| 12  |          | 146.6       | 5.0          |
| 13  |          | 149.6       | 3.0          |
| 14  |          | 155.6       | 6.0          |

---

Figure 3: Location of experimental coal mine and the geologic columns.
Substitute Equations (1) and (2) into Equation (3) to adjust the actual weight of water in the model.

\[ m'_{w} = m_{w} - m_{b}' \times a, \]  

(3)

where \( m'_{w} \) is the weight of water required after model correction and \( m_{w} \) is the weight of water required before model correction.

The weight and moisture content of sand and the weight of water in Table 1 were substituted into Equations (2) and (3); the experimental material ratio of each stratum in the model is corrected and shown in Table 2. The material ratio applied in establishing the physical similar similarity model is shown in Table 2.

The air-drying time of the physical similarity model had an important impact on its physical properties. Therefore, a 20.9 m thick fine sandstone was taken as the research object; 60 cylindrical samples with a diameter of 50 mm and a height of 100 mm were prepared and cured in the same environment as the physical similarity model. The variation characteristics of sample strength with air-drying time are shown in Figure 5, it could be seen that when the sample was left to air dry for 18 days, and its compressive strength reached 200 kPa, which was almost consistent with simulated compressive strength of fine sandstone. Therefore, the model could be excavated at this time.

### Table 1: Proportion of materials for physical similarity model.

| Number | Lithology     | Thickness (m) | Simulated thickness (cm) | Simulated strength (kPa) | Sand (kg) | Calcium carbonate (kg) | Gypsum (kg) | Water (kg) |
|--------|---------------|---------------|--------------------------|--------------------------|-----------|-------------------------|-------------|------------|
| 1      | Loess         | 34.2          | 22.8                     | 0.2                      | 179.55    | 17.96                   | 7.69        | 22.8       |
| 2      | Mudstone      | 11.0          | 7.3                      | 70.0                     | 57.49     | 5.75                    | 2.46        | 7.3        |
| 3      | Coarse sandstone | 31.3      | 20.9                     | 174.4                    | 161.23    | 8.06                    | 18.81       | 20.9       |
| 4      | Mudstone      | 3.5           | 2.2                      | 70.0                     | 17.33     | 1.73                    | 0.74        | 2.2        |
| 5      | Fine sandstone| 5.0           | 3.3                      | 202.0                    | 22.28     | 3.71                    | 3.71        | 3.3        |
| 6      | Sandy mudstone| 14.2          | 9.5                      | 103.2                    | 74.81     | 5.34                    | 5.34        | 9.5        |
| 7      | Mudstone      | 16.9          | 11.3                     | 70.0                     | 89.0      | 8.9                     | 3.8         | 11.3       |
| 8      | Siltstone     | 4.9           | 3.3                      | 180.0                    | 25.46     | 1.27                    | 2.97        | 3.3        |
| 9      | Mudstone      | 5.8           | 3.9                      | 70.0                     | 30.71     | 3.07                    | 1.32        | 3.9        |
| 10     | Siltstone     | 12.8          | 8.5                      | 180.0                    | 65.57     | 3.28                    | 7.65        | 8.5        |
| 11     | Mudstone      | 2.0           | 1.3                      | 70.0                     | 10.24     | 1.02                    | 0.44        | 1.3        |
| 12     | #2 coal seam  | 4.0           | 2.6                      | 63.2                     | 20.48     | 2.05                    | 0.87        | 2.6        |
| 13     | Sandy sandstone| 3.0          | 2.0                      | 129.2                    | 15.75     | 0.68                    | 1.57        | 2.0        |

### Figure 4: Weights of sand samples before and after dehydration. (a) Samples of sand before dehydration. (b) Samples of sand after dehydration.
similarity model process mainly included the displacement and the WFF development of overlying strata. After the model was laid and air dried, the marked points were sprayed on the model surface, and the marked points were unevenly and irregularly distributed. The Vic 2D noncontact full field strain measurement system was used to identify the marked points on the model. The system used a Vic digital image correlation algorithm to compare and analyze the position variation of identification points to monitor the displacement variation of the whole model. The Vic 2D system mainly included AVT industrial camera, lighting system, and Vic 2D system. Meanwhile, the development range of WFF of the model was monitored by a high speed camera, measuring scale, and other equipment.

**Table 2: Corrected proportion of materials for physical similarity model.**

| Number | Lithology         | Thickness (m) | Simulated thickness (cm) | Simulated strength (kPa) | Sand (kg) | Calcium carbonate (kg) | Gypsum (kg) | Water (kg) |
|--------|-------------------|---------------|--------------------------|--------------------------|-----------|------------------------|-------------|------------|
| 1      | Loess             | 34.2          | 22.8                     | 0.2                      | 188.31    | 17.96                  | 7.69        | 14.04      |
| 2      | Mudstone          | 11.0          | 7.3                      | 70.0                     | 60.29     | 5.75                   | 2.46        | 4.5        |
| 3      | Coarse sandstone  | 31.3          | 20.9                     | 174.4                    | 169.09    | 8.06                   | 18.81       | 13.04      |
| 4      | Mudstone          | 3.5           | 2.2                      | 70.0                     | 18.17     | 1.73                   | 0.74        | 1.36       |
| 5      | Fine sandstone    | 5.0           | 3.3                      | 202.0                    | 23.37     | 3.71                   | 3.71        | 2.21       |
| 6      | Sandy mudstone    | 14.2          | 9.5                      | 103.2                    | 78.46     | 5.34                   | 5.34        | 5.85       |
| 7      | Mudstone          | 16.9          | 11.3                     | 70.0                     | 93.34     | 8.9                    | 3.8         | 6.96       |
| 8      | Siltstone         | 4.9           | 3.3                      | 180.0                    | 26.7      | 1.27                   | 2.97        | 2.06       |
| 9      | Mudstone          | 5.8           | 3.9                      | 70.0                     | 32.21     | 3.07                   | 1.32        | 2.4        |
| 10     | Siltstone         | 12.8          | 8.5                      | 180.0                    | 68.77     | 3.28                   | 7.65        | 5.3        |
| 11     | Mudstone          | 2.0           | 1.3                      | 70.0                     | 10.74     | 1.02                   | 0.44        | 0.8        |
| 12     | Coal seam         | 4.0           | 2.6                      | 63.2                     | 21.48     | 2.05                   | 0.87        | 1.6        |
| 13     | Sandy sandstone   | 3.0           | 2.0                      | 129.2                    | 16.52     | 0.68                   | 1.57        | 1.23       |

**Figure 5: Variation characteristics of sample strength with time.**
3.2. Backfill Similar Material Design. In order to ensure the accuracy of physical similar simulation test, the stress-strain process of backfill similar materials and original backfilled gangue materials should be similar. In order to simulate the original action process of backfilled gangue materials, the original gangue materials were screened on site, the screened gangue materials was placed in the self-made steel barrel, and the stress-strain characteristics of original gangue materials under different grading size schemes were tested and analyzed. Since the backfill ratio of experimental SBBM working face was 80%, therefore, the stress-strain characteristic was selected whose stress reached 3.5 MPa and the strain reached 0.2, and this scheme would be compared with similar backfill materials in the later stage. Based on the similar conditions and simulation experience [26, 27], paper, pearl cotton, sponge, board, and other materials were determined to prepare the combined similar backfill materials, whose stress-strain characteristics were carried out by compaction tests. Furthermore, compared with the stress-strain curves of original gangue materials and different similar backfill materials, it was determined that the optimal combination of similar backfill materials was as follows: 5 mm thick pearl sponge + 5 mm thick sponge + 10 mm thick paper + 6 mm thick board (the simulated stress reached 14 kPa, and the strain reached 0.2). The comparison of the stress-strain relationship between similar backfill materials and original gangue materials is shown in Figure 7.

3.3. Comparative Analysis of Control Effect of WFF Development. According to the scheme of physical similar simulation test, the coal seam in the same area was mined by SBCM and SBBM, respectively. The characteristics of deformation and WFF development above gob using different mining methods were analyzed. The excavation of the models was fully consistent with the above two mining technologies.

3.3.1. Deformation Characteristics of Physical Similarity Models. The deformation nephograms of overlying strata using SBCM and SBBM were obtained by Vic-2D noncontact full field strain monitoring system and are shown in Figure 8. Herein, the x-axis direction was the excavation direction in the model. As observed, when the coal seam was excavated, from the perspective of color variation of the nephogram, compared with SBCM, the variation color difference gradient of SBBM was smaller, and the variation of nephogram was relatively moderate, which showed that the amount and range of deformation of overlying strata by SBBM were smaller. Meanwhile, basic roof and main key stratum were taken as the research objects, as shown in Figure 9; obvious subsidence deformation occurred in the basic roof and the main key stratum above the SBCM working face. However, after the coal seam was recovered by SBBM, the subsidence deformation of the basic roof above the SBBM working face was reduced by 86.6%, and the subsidence deformation of the main key stratum was reduced by 27.8%. It could be seen that when the gangue materials were filled into the gob, the subsidence space of overlying strata was reduced and the deformation of overlying strata above the gob was effectively controlled.

3.3.2. WFF Development Characteristics of Physical Similarity Models. During the observation process in physical similar simulation test, it could be found that the use of backfill materials reduced the damage range of overlying strata and restricted the WFF development of overlying strata. Figure 10 shows the characteristics of WFF development using different coal mining methods. It could be seen that when SBCM was used to recover coal seams, the height
of water-flowing fractured zone was 30.3 cm, the basic roof was completely damaged, and the highest position of the abscession layer was about 43.3 cm. When SBBM was used, the height of water-flowing fractured zone by coal mining was only 5.3 cm, the basic roof was partially damaged, and the highest position of the abscession layer was about 28.3 cm, which effectively controlled the WFF development.

In addition, the activity range of overlying strata caused by SBCM was 145 × 120 × 43 cm, while the activity range of overlying strata caused by SBBM was reduced to 145 × 118 × 28 cm, which greatly controlled the activity range of overlying strata and fundamentally changed the stress distribution of the whole surrounding rock stress distribution.

3.3.3. Comparison and Analysis of Test Results. According to the above analysis, the damage in overlying strata caused by SBBM was much smaller than that caused by SBCM. The comparison results of deformation of overlying strata, height of water-flowing fractured zone, and activity range of overlying strata using SBCM and SBBM are shown in Table 3. It could be seen that after the recovery of the experimental mining area, the maximum vertical deformation of overlying strata caused by SBBM was reduced from 28.8 cm of the SBCM to 2.48 cm, with a decrease of 91.4%. The height of water-flowing fractured zone caused by SBBM method decreased from 30.3 cm of SBCM to 5.3 cm, with a decrease of 82.5%. The activity range of overlying strata caused by SBBM was reduced from 5737.3 cm² of SBCM to 3721.5 cm², with a decrease of 64.9%. The results showed the gangue materials were filled into the gob as the backfilling body, which reduced the subsidence space of the overlying strata. Meanwhile, the gangue materials and the protective coal pillar were performed as the bearing body to support the overlying strata. It played a significant role in controlling damage range and WFF development of overlying strata. The SBBM method solved the problem of water
Figure 9: Displacement of strata of physical similarity models. (a) Basic roof. (b) Main key stratum.

Figure 10: Characteristics of WFF development using different coal mining methods. (a) SBCM method. (b) SBBM method.
resource loss caused by coal mining under aquifer with low horizon; then, the purpose of water resource protection would be finally achieved.

4. Mechanism of Control Effect of WFF Development Using SBBM

According to the results of physical simulation test, in SBCM process, under the action of vertical and horizontal stress, the overlying strata above the gob would be damaged and bending subsidence; “three zones” would be formed in the vertical direction, namely, caving zone, fractured zone, and bending subsidence zone. If the location of aquifer was low, it might be located in the formed caving zone or formed fractured zone after coal mining, which would cause a large loss of water resource, thus seriously affecting the working face and the ecological environment of the coal mine. SBBM was different from SBCM; when the coal seam had been mined, gangue materials were immediately filled into the gob; the bulldozer was used to compact the gangue materials so that it could effectively support the immediate roof. With the advancement of working face, under the gravity of overlying strata, the backfilled gangue materials could not provide sufficient support due to its large porosity, the backfilling body (gangue materials) was gradually compacted, and then, the roof would be deformed slowly. When the backfilled gangue materials of the gob were4 compacted to a certain extent, there would be no subsidence of the overlying strata, and only “two zones” were formed in the vertical direction above, namely, fractured zone and bending subsidence zone, without the caving zone. It could be seen that in the process of SBBM, after the gangue materials were filled into the gob as the backfilling body, it would be the permanent bearing body, which bore the load of the overlying strata accompanied with the protective coal pillar. In addition, the gangue materials filled into the collapse space of the overlying strata, which was equivalent to reduce the mining height, so as to greatly reduce the subsidence and failure height of the overlying strata, and reduced the activity range of overlying strata. Further, the SBBM method effectively restricted the WFF development, which ensured the integrity of the low-level stratum and low-level aquifer, so as to achieve the purpose of water resource protection.

5. Prevention System of Water Resource Loss

The above analysis showed that SBBM had an obvious control effect on WFF development and water resource protection. The research showed that the higher the backfill ratio, the better the overlying strata deformation control effect and then the better the WFF developmental control effect, which could prevent the WFF to reach to aquifer, thus preventing the loss of water resources caused by coal mining. If the backfill ratio of SBBM was required to reach a designed index, it was much important to monitor in real time the backfill ratio of working face during coal mining. On the other hand, considering the damage of overlying strata and protective coal pillar caused by coal mining were inevitable. Therefore, it could be supplemented from many aspects, such as reinforcement of protective coal pillar, monitoring of protective coal pillar deformation, and monitoring of height of water-flowing fractured zone, so as to ensure that water resources would not be lost and the safety of the working face in recovering process of coal seam under aquifer. To sum up, it could be determined that the prevention system was mainly based on the monitoring backfill ratio in real time (main control measures) and supplemented by reinforcement and monitoring of working face (auxiliary measures). Figure 11 shows the prevention system of water resource loss.

In terms of monitoring deformation and reinforcement of the protective coal pillar, the stress meters were embedded in the protective coal pillar to monitor the stress change. At the same time, the roof subsidence and the deformation of the protective coal pillar were monitored in real time by means of fiber Bragg grating sensors and ultrasonic range finder sensor. The dangerous area could be supported by increasing the support strength (increasing the support density of bolts and anchors), and the stability of the coal pillar could be strengthened by grouting in the coal pillar. In terms of height of WFF monitoring, observation of washing fluid loss and drilling TV imaging were used to monitor the height of water-flowing fractured zone, and the water level change of aquifer was recorded in real time by water level monitoring recorder; this data was obtained by the above measurement, which could judge whether the SBBM working face was in a safe and stable state. The control of WFF development and protection of water resource could be achieved by increasing the backfill ratio and the width of protective coal pillar. In the actual SBBM process, only the main control measures and auxiliary measures were adopted at the same time; could the safety and stability of SBBM working face and the protection of water resource in coal mine be realized?

6. Future Works

Based on the technical characteristics of SBBM technology, this study represented only the control mechanism of WFF development using SBBM, which used the methods of physical similarity simulation test and theoretical analysis. However, there might be some potential limitations in this study,
like monitoring techniques and methods were single, which reduced the test accuracy relatively. Therefore, for the future works, the more techniques can be used, like the BOTDA system, the AE system, the drilling peep method, mechanical calculation method, and numerical calculation method. Meanwhile, the focus of the future research is the engineering design of protective coal pillar and backfill ratio of SBBM working face, which can bring the related parameters of SBBM working face to the optimal value under the water resource protection in coal mine.

7. Conclusions

(1) Based on the characteristics of SBBM technology and the material ratio after model correction, the physical similarity models for comparing the control effects of WFF development using SBCM and SBBM were established. It was obtained that the strength of the model could reach the simulated compressive strength when the model was left to air dry for 18 days; the model could be excavated at this time. Meanwhile, displacement and the WFF development of overlying strata were monitored in excavating physical similarity model process

(2) According to physical similarity criterion, paper, pearl cotton, sponge, board, and other materials were determined to prepare the combined similar backfill materials, and the laboratory compaction characteristic matching test was carried out. Through comparing with the stress-strain curves of original gangue materials and different similar backfill materials, it was determined that the optimal combination of similar backfill materials was as follows: 5 mm thick pearl sponge + 5 mm thick sponge + 10 mm thick paper + 6 mm thick board (the simulated stress reached 14 kPa, and the strain reached 0.2)

(3) The gangue materials were filled into the gob as the backfilling body; it would be the permanent bearing body, which bore the load of the overlying strata accompanied with the protective coal pillar. In addition, the gangue materials filled into the collapse space of the overlying strata, which was equivalent to reduce the mining height, so as to greatly reduce the subsidence and failure height of the overlying strata, and reduced the activity range of overlying strata. Compared with the SBCM, the maximum vertical deformation, the height of water-flowing fracture zoned, and activity range of overlying strata using SBBM were decreased by 91.4%, 82.5%, and 64.9%, respectively. The SBBM played a significant role in controlling damage and WFF development of overlying strata and could achieve the purpose of water resource protection

![Figure 11: Prevention system of water resource loss.](image-url)
(4) From the perspective of control of WFF development using SBBM, the prevention system of water resource loss mainly based on monitoring backfill ratio in real-time (main control measures) and supplemented by reinforcement and monitoring of working face (auxiliary measures) was proposed, so as to realize the safety and stability of SBBM working face and the protection of water resources in coal mine.

Data Availability
The relevant data used in this paper are available from the authors upon request.

Conflicts of Interest
The authors declare no conflicts of interest.

Acknowledgments
This research was funded by the National Natural Science Foundation of China (52004201), China Postdoctoral Science Foundation (2020M683677XB and 2021T140551), and Natural Science Foundation of Shaanxi Provincial Department of Education (20JK0765).

References
[1] F. Liu, W. J. Cao, J. M. Zhang, G. M. Cao, and L. F. Guo, "Current technological innovation and development direction of the 14th five-year plan period in China coal industry," Journal of China Coal Society, vol. 46, no. 1, pp. 1–15, 2021.
[2] G. X. Ye, F. X. Jiang, P. L. Liu, Z. Q. Feng, and D. Z. Wang, "Design and optimization of efficient mining technology in boundary coal recovery," Journal of University Science & Technology Beijing, vol. 29, no. 7, pp. 655–659, 2007.
[3] Y. Zhang, S. G. Cao, N. Zhang, and C. Z. Zhao, "The application of short-wall block back filling mining to preserve surface water resources in Northwest China," Journal of Cleaner Production, vol. 261, article 121232, 2020.
[4] D. S. Zhang, G. W. Fan, L. Q. Ma, and X. F. Wang, "Aquifer protection during longwall mining of shallow coal seams: a case study in the Shandong coalfield of China," International Journal of Coal Geology, vol. 86, no. 23, pp. 190–196, 2011.
[5] Y. H. Wu, L. S. Cheng, L. Q. Ma et al., "A transient two-phase flow model for production prediction of tight gas wells with fracturing fluid-induced formation damage," Journal of Petroleum Science and Engineering, vol. 199, article 108351, 2021.
[6] H. Wu, D. Ma, and A. J. S. Spearling, "Fracture phenomena and mechanisms ofbrittle rock with different numbers of openings under uniaxial loading," Geomechanics and Engineering, vol. 25, no. 6, pp. 481–493, 2021.
[7] G. W. Fan and D. S. Zhang, "Mechanisms of aquifer protection in underground coal mining," Mine Water & the Environment, vol. 34, no. 1, pp. 95–104, 2015.
[8] H. Yan, J. X. Zhang, N. Zhou, and M. Li, "Application of hybrid artificial intelligence model to predict coal strength alteration during CO2 geosequestration in coal seams," Science of the Total Environment, vol. 711, article 135029, 2020.
[9] Y. Wu, L. Cheng, J. Killough et al., "Integrated characterization of the fracture network in fractured shale gas Reservoirs–Stochastic fracture modeling, simulation and assisted history matching," Journal of Petroleum Science and Engineering, vol. 205, 2021.
[10] H. Liu, X. Rao, and H. Xiong, "Evaluation of CO2 sequestration capacity in complex-boundary-shape shale gas reservoirs using projection-based embedded discrete fracture model (pEDFM)," Fuel, vol. 277, article 118201, 2020.
[11] J. X. Zhang, B. Y. Li, N. Zhou, and Q. Zhang, "Application of solid backfilling to reduce hard-roof caving and longwall coal face burst potential," International Journal of Rock Mechanics and Mining Sciences, vol. 88, pp. 197–205, 2016.
[12] H. Xiong, D. Devegowda, and L. L. Huang, "EOR solvent-oil interaction in clay-hosted pores: insights from molecular dynamics simulations," Fuel, vol. 249, pp. 233–251, 2019.
[13] X. X. Miao, A. Wang, Y. J. Sun, L. G. Wang, and H. Pu, "Research on basic theory of mining with water resources protection and its application to arid and semi-arid mining areas," Chinese Journal of Rock Mechanics and Engineering, vol. 28, no. 2, pp. 217–227, 2009.
[14] J. L. Xu, W. B. Zhu, and X. Z. Wang, "Study on water-inrush mechanism and prevention during coal mining under unconsolidated confined aquifer," Journal of Mining & Safety Engineering, vol. 28, no. 3, pp. 333–339, 2011.
[15] J. L. Xu, X. Z. Wang, W. T. Liu, and Z. G. Wang, "Effects of primary key stratum location on height of water flowing fracture zone," Chinese Journal of Rock Mechanics & Engineering, vol. 28, no. 2, pp. 381–385, 2009.
[16] X. X. Miao, R. H. Chen, and H. N. Bai, "Fundamental concepts and mechanical analysis of water-resisting key strata in water-preserved mining," Journal of China Coal Society, vol. 32, no. 6, pp. 561–564, 2007.
[17] L. M. Fan, X. D. Ma, and R. J. Ji, "Progress in engineering practice of water-preserved coal mining in western eco-environment frangible area," Journal of China Coal Society, vol. 40, no. 8, pp. 1711–1717, 2015.
[18] L. M. Fan, "Scientific connotation of water-preserved mining," Journal of China Coal Society, vol. 45, no. 1, pp. 667–674, 2017.
[19] J. X. Zhang, J. Li, T. L. An, and Y. L. Huang, "Deformation characteristic of key stratum overburden by raw waste backfilling with fully-mechanized coal mining technology," Journal of China Coal Society, vol. 35, no. 3, p. 357, 2010.
[20] J. X. Zhang, H. Q. Jiang, X. J. Deng, and F. Ju, "Prediction of the height of the water-conducting zone above the mined panel in solid backfill mining," Mine Water & the Environment, vol. 33, no. 4, pp. 317–326, 2014.
[21] H. Yan, J. X. Zhang, N. Zhou, S. Zhang, and X. J. Dong, "Shaft failure characteristics and the control effects of backfill body compression ratio at ultra-contiguous coal seams mining," Environmental Earth Science, vol. 77, no. 12, p. 458, 2018.
[22] Y. L. Huang, J. X. Zhang, Q. Zhang, S. J. Nie, and B. F. An, "Strata movement control due to bulk factor of backfilling body in fully mechanized backfilling mining face," Journal of Mining & Safety Engineering, vol. 29, no. 2, pp. 162–167, 2012.
[23] Y. L. Huang, J. M. Li, T. Q. Song, G. Q. Kong, and M. Li, "Analysis on filling ratio and shield supporting pressure for overburden movement control in coal mining with compacted backfilling," Energies, vol. 10, no. 1, p. 31, 2017.
[24] W. L. Shen, G. C. Shi, Y. G. Wang, J. B. Bai, R. F. Zhang, and X. Y. Wang, "Tomography of the dynamic stress coefficient
for stress wave prediction in sedimentary rock layer under the mining additional stress,” *International Journal of Mining Science and Technology*, vol. 31, pp. 653–663, 2021.

[25] J. M. Li, Y. L. Huang, H. Pu et al., “Influence of block shape on macroscopic deformation response and meso-fabric evolution of crushed gangue under the triaxial compression,” *Powder Technology*, vol. 384, pp. 112–124, 2021.

[26] Y. P. Wu, B. S. Hu, D. Lang, and Y. P. Tang, “Risk assessment approach for rockfall hazards in steeply dipping coal seams,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 138, article 104626, 2021.

[27] H. Yan, J. X. Zhang, B. Y. Li, and C. L. Zhu, “Crack propagation patterns and factors controlling complex crack network formation in coal bodies during tri-axial supercritical carbon dioxide fracturing,” *Fuel*, vol. 286, article 119381, 2021.