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Research Article

Study on Layered-Backfill-Based Water Protection Technology of Thick Coal Seam in the Ecologically Fragile Mining Area in Western China

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The mining areas in Western China are characterized by water shortage and ecological fragility, and the coal resources in these areas are extracted in a large-scale and highly intensive manner, which is highly likely to induce ecological problems, such as soil erosion and grassland degradation. In addition, there is a secondary protection zone of Hongshixia water source near Guojiatan minefield. If the water resources loss of Salawusu Formation is too large, it will affect the normal water supply of Yulin city. To reasonably coordinate coal exploitation and water protection, the development characteristics of water-conducted fissures with different backfill ratios are obtained in combination with theoretical analysis, field test, and numerical modelling. The panel layout of the layered-backfill-based water protection working face and the parallel operation of mining and backfilling are designed, and a feedback regulation system integrating hydrological monitoring and backfill ratios is established, which assists in evaluating the effectiveness of water protection. The results indicated that when the slicing mining method was adopted with the roof naturally caving, the maximum development height of the water conducted fracture zone was 220.0 m (developed to the Yan'an Formation), and the water conducted fracture zone could only develop to the Yan'an Formation without crossing the Zhiluo Formation when the backfill ratio reached 80%. The water emission rates in the west of the field testing area reduced from 334.95 m^3/h to 60.60 m^3/h, dropping by 86.86%. Compared to the scene prior to the layered backfill mining, the shallow water outflow was reduced by 72.74 m^3/h, and it helped annually reduce the shallow water loss of 637200 m^3, which was equivalent to 1.74% of the actual water supply to Yunli city every year. The results of this study can provide guidance on effectively avoiding the loss of shallow water resources that are regarded as indispensable sources of domestic water.

1. Introduction

Based on the characteristics of China's energy endowment, it is estimated that coal will still contribute to more than 50% of primary energy by 2030 and remain China's leading energy for a long time. As the coal mining industry center of gravity shifts to western China, the coal production output in this region has accounted for more than 70% of the total production, which plays an indispensable role in ensuring national energy security. However, the western inland area where the coal resources are distributed is characterized by a typical ecologically fragile area, with low rainfall, huge evaporation, and highly scarce water resources [1–3]. Coal resources are exploited in a large-scale and high-intensity manner, which increases the possibility of inducing ecological problems, such as soil erosion and grassland degradation [4–6]. As a result, coal mining in western ecologically fragile areas is facing increasing threats from resolving the contradiction between coal resource exploitation and water resource protection and reaching a reasonable balance.

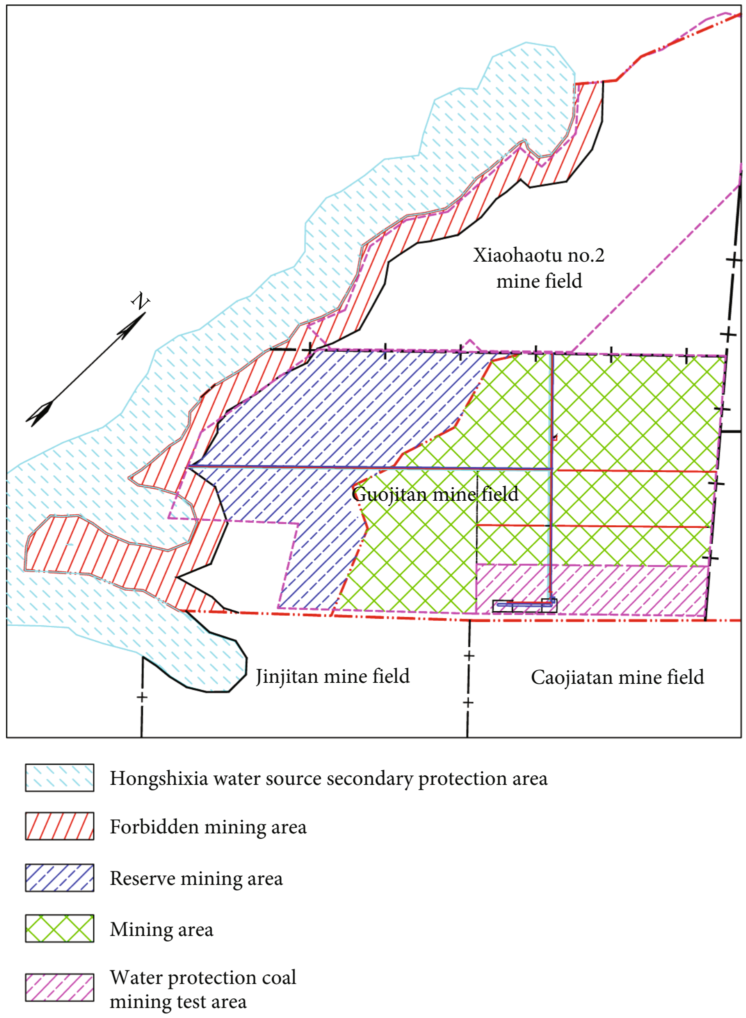


Figure 1: Relative location of minefield and water preservation area.

At present, much valuable research on water conservation and coal mining in the ecologically fragile mining areas in western China has been conducted by many scholars. Wang et al. [7–10] solved the key scientific problems of reducing the loss of coal resources during coal mining in ecologically vulnerable areas in western China and correspondingly established an integrated technical system. Fan et al. [11–13] reviewed the noticeable environmental problems arising from coal mining in northern Shaanxi, such as land desertification and the contradiction between the supply and demand of water resources. Yu et al. [14, 15] analyzed the evolution characteristics of the water-conducting fractured zone in the overlying strata in the process of slicing mining and obtained the distribution patterns of the water-conducting fractured zone. Zhang et al. [16–18] investigated the influence of short-wall block backfill mining on the water-conducting fractured zone and surface subsidence and evaluated the effectiveness of short-wall block backfill mining for water protection. Zhang et al. [19–21] thoroughly studied the mining-induced failure characteristics of rock-soil layer and water aquifers by means of solid-liquid coupled similar material simulation platform and failure theory of rock strata, and the results provided guidance on effectively preventing water-conducting fracture zone from developing towards and connecting with the water-resisting layer. Zhang et al. [22] regarded the overlying rock strata as a whole structure and adopted different mining technologies targeted at different water blocking properties of the overall overlying strata structure, which assisted in fulfilling the purpose of coal mining with water protection. Ma et al. [23–25] studied the development law of water conducting fissures in mining overburden in Northern Shaanxi mining area, determined the thickness of protective layer, and analyzed mining methods such as height limited mining, filling mining, and narrow strip mining.

The above research results have played a significant role in promoting the development of water-preserving coal mining in ecologically fragile mining areas in western China and providing theoretical support and valuable experience for water-preserving mining in many coal mines. However, the above research mainly focuses on water retaining coal mining from the perspective of the stability of the aquifuge. It is not analyzed in combination with factors such as shallow water overflow and surface water loss. As a result, this paper studies the effect of backfill mining under layered seam conditions on the water emission and the water overflow of the Salawusu Formation, based on site-specific geological mining conditions of Guojiatan coal mine. A reasonable backfill ratio is determined to control the water emission and reduce water overflow of the Salawusu Formation. Reduce the loss of water resources with water supply significance on the surface, ensure the water supply capacity of Hongshixia water source, and ensure the water supply safety of Yulin city [26].

2. Significance of Water Protection Mining

2.1. Overview of Mining Conditions. Guojiatan minefield is located southwest of the phase III planning area of the Yushen mining area in Jurassic Coalfield in Northern Shaanxi. There is a Hongshixia graded II water preservation area outside the southwest boundary of the minefield, which is the primary water supply source in Yulin City, accounting for nearly 90% of the total water supply. The relative position of the minefield and the water preservation area is shown in Figure 1.

According to the overall planning of the mining area, the Guojiatan minefield is divided into a reserved area, a mining area, and a testing area. In accordance with the principles of being far away from the Hongshixia water preservation area and controlling the risk step by step, the preliminary testing area is designated. The testing area is 8.1 km long and 1.7 km wide, with an area of 14.03 km^2. The amount of resource reserves in this testing area is 192.11 Mt, and the designed recoverable reserves of 2^{-2} coal seams are 95.01 Mt.

The roof strata of 2^{-2} coal seam in this testing area mainly contains fine-grained sandstone, coarse-grained sandstone, and siltstone, above which Baode laterite water blocking layer exists. The comprehensive histogram of this area is shown in Figure 2.

The analysis of hydrogeological conditions indicated that the water resources are mainly sourced from pore phreatic water of Salawusu Formation and confined water of bedrock pores and fissures of Zhiluo Formation and Yan'an Formation. As the fracture zone only develops to the bedrock strata and a laterite aquifer exists, the phreatic pore water of the Salawusu Formation is considered one of the indirect water filling aquifers, and Zhiluo Formation and Yan'an Formation are the direct water filling aquifers. The normal water emission predicted by the "corridor method" is 1596 m^3/h, with a maximum emission rate of 1915 m^3/h.

2.2. Connotation and Necessity Analysis. In a narrow sense, the purpose of water protection coal mining is to protect the structural integrity of the aquifer and the stability of the water-blocking strata underlying the aquifer. The water-blocking strata do not destabilize or crack during the coal mining process and maintain their water-resistance function, which ensures the goal of water preserving coal mining can be achieved [12, 27]. The onsite measured data in some coal mines in the Yushen mining area indicated that although the water-preserving coal mining technology was employed and the stability of the water-blocking strata was

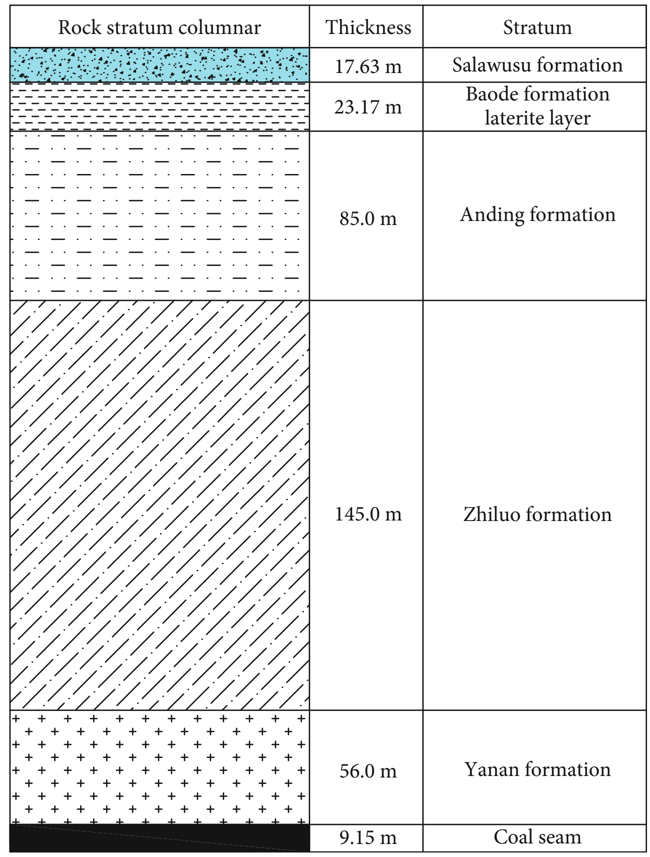


Figure 2: Comprehensive histogram of the testing area with water-protection mining.

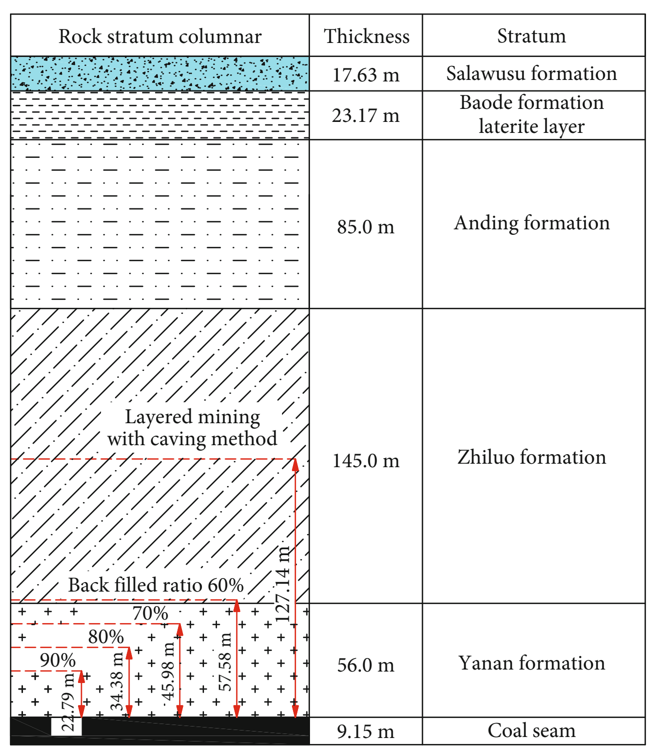


Figure 3: Theoretical calculation results of the height of the water-conducting fractured zone under different mining conditions.

Table 1: Summary of field testing results of the water-conducting fractured zone in the Yushen mining area and the adjacent mining areas.

Mining area		Coal mine	Working face length (m)	Depth of cover (m)	Mining method	Mining height (m)	Height of water-conducting fractured zone (m)	Fracturing-mining ratio
Yushen mining area	I	Jinjitan coal mine	300	229.6~262.1	Slice mining	5.5	110.14~143.37	20.03~26.07
			300	243.6~253.4	Full-height mining at one time	5.3~7.5	133.45~167.5	22.33~25.18
		Xuemiaotan coal mine	281.6	210	Fully mechanized mining	5.7	106–124	18.6~21.8
		Hanglaiwan coal mine	300	253	Slice mining	4.5	93.87~114.38	20.86~25.42
			300	230	Slice mining	5.0	110.3~124.8	22.06~23.51
		Caojiatan coal mine	360	269.8~273.4	Slice mining	6.0	136.1~139.15	22.68~23.19
		Yushuwan coal mine	255	284~291	Slice mining	5.0	117.8~135.4	23.56~27.08
	II	Jinjie coal mine	370	108~124	Fully mechanized mining	3.5	45.7	13.1
	III	Longde coal mine	300	201.04~202.80	Fully mechanized mining	3.96	69.4~76.85	17.53~19.41
		Xiaobaodang no.1 coal mine	350	295~310	Fully mechanized mining	5.8	152.01~158.78	26.21~27.38
Yuheng north mining area		Yuyang coal mine	200	182~216	Fully mechanized mining	3.5	84.8~96.3	24.0~27.5
Hujierte mining area		Bayangaole coal mine	260	610	Fully mechanized mining	5.3	126	23.7
		Menkeqing coal mine	300	689	Fully mechanized mining	4.7	110	23.4

sustained, the shallow water aquifer recharges the direct water-filled aquifer underneath through the form of overflow as a result of the special hydrogeological conditions in this region, which indirectly leads to the loss of water resources in the surface Salawusu Formation [28]. The mine water source was identified in the production mines with similar hydrogeological conditions near the Guojiatan minefield (Caojiatan coal mine, Jinjitan coal mine, and Xiaobaodang coal mine) by isotope method. The results showed that shallow water accounted for 7.0%~25.0%, and the Jinjitan coal mine lost approximately 2.2 million m^3/a of Quaternary shallow water resources every year, which took up approximately 6% of the actual water supply of the concentrated water sources in the urban area of Yulin City and meant a huge amount of water loss.

However, from the perspective of water-preserving coal mining in a broad sense, the mine water emission should be controlled while protecting the stability of the water-blocking strata underlying the aquifer. In addition, it was essential to coordinate the relationship between coal resource mining and groundwater resource protection and reduce the loss of Quaternary shallow water resources, which could ensure a stable water supply from the Hongshixia water source.

3. Evolution Characteristics of the Water-Conducting Fractured Zone with Different Backfilled Ratios

3.1. Theoretical Calculation. According to the standard for exploration and evaluation of hydrogeology, engineering geology, and environmental geology of coal deposits (MT/T1091-2008), the height of the water-conducting fractured zone can be determined as follows [29–31]:

$$H = \frac{100M}{(2.4n + 2.1) + 11.2}, \quad (1)$$

where H is the maximum height of the water-conducting fractured zone, m; M is cumulative mining thickness; and n is the number of coal mining layers.

The thickness of the coal seam in the water-preserving mining area is 9.15 m. According to the preliminary design of the mine, the slicing mining method is applied to extract the 2^{-2} coal seam, with a mining height of 5.0 m and 3.0 m for the upper layer and lower layer, respectively. Particularly, the coal seam with a thickness of 1.15 m is reserved at the top of the mining seam. When the roof area above the mined-out seam is allowed to collapse naturally, the maximum developing height of the water-conducting fractured zone is 127.14 m. The maximum developing heights of the water-conducting fractured zone in the process of mining the 2^{-2} coal seam were 57.58 m, 45.98 m, 34.38 m, and 22.79 m, respectively, with a backfill ratio of 60%, 70%, 80%, and 90%, as illustrated in Figure 3.

3.2. Analogy Analysis of Field Testing Results. The onsite monitoring of the developing height of the water-conducting fractured zone was conducted by means of surface drilling

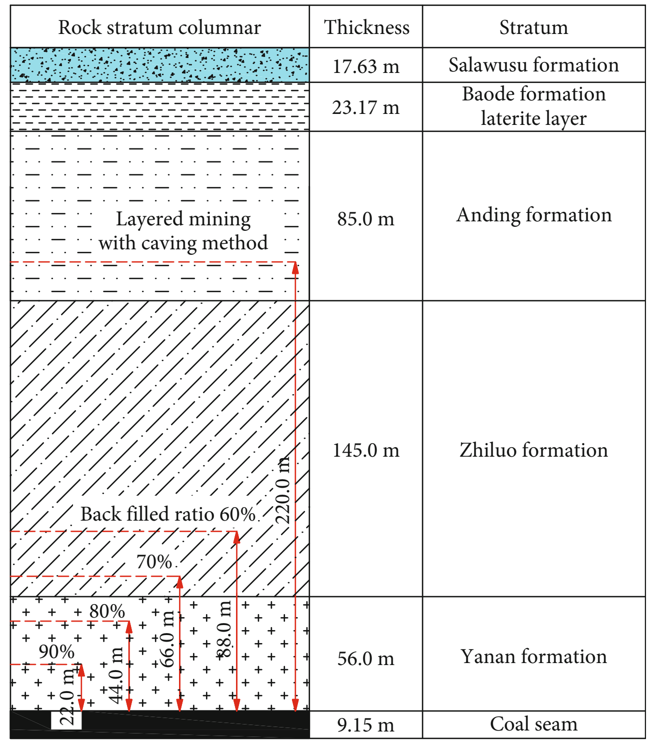


Figure 4: Analogy results of the height of the water-conducting fractured zone under different mining conditions.

method, borehole telemetric method, underground drilling method, and physical exploration method. The measured results of the height of the water-conducting fractured zone are listed in Table 1 for the coal mines located in the Yushen mining area at phase I, phase II, and phase III and the Hujierte mining area adjacent the western boundary of the Yushen mining area [32–36].

The onsite measured results indicated that the fracturing-mining ratios were in the range of 18.6~27.78, 13.1, 17.53~27.38, and 24.0~27.5 for the Yushen mining area at phase I, phase II, and phase III and the northern Yushen mining area, respectively.

The operating coal mines in the vicinity of the Guojiatan minefield mainly include the Jinjitan, Caojiatan, and Xiaobaodang no. 1 coal mines, whose strata structures and depth of cover are similar to those of the Guojiatan coal mine. As a result, the fracturing-mining ratio for the Guojiatan coal mine was determined as 27.5 by choosing the maximum fracturing-mining ratios measured for the Jinjitan, Caojiatan, and Xiaobaodang no. 1 coal mines.

When the caving method was adopted for the layered mining seam, the maximum developing height of the water-conducting fractured zone was 220.0 m. The maximum heights of the water-conducting fractured zone were 88.0 m, 66.0 m, 44.0 m, and 22.0 m for the backfill ratio of 60%, 70%, 80%, and 90%, respectively, as shown in Figure 4.

3.3. Numerical Simulation Analysis

3.3.1. Model Construction. Numerical simulation software termed UDEC was used to study the evolution characteristics

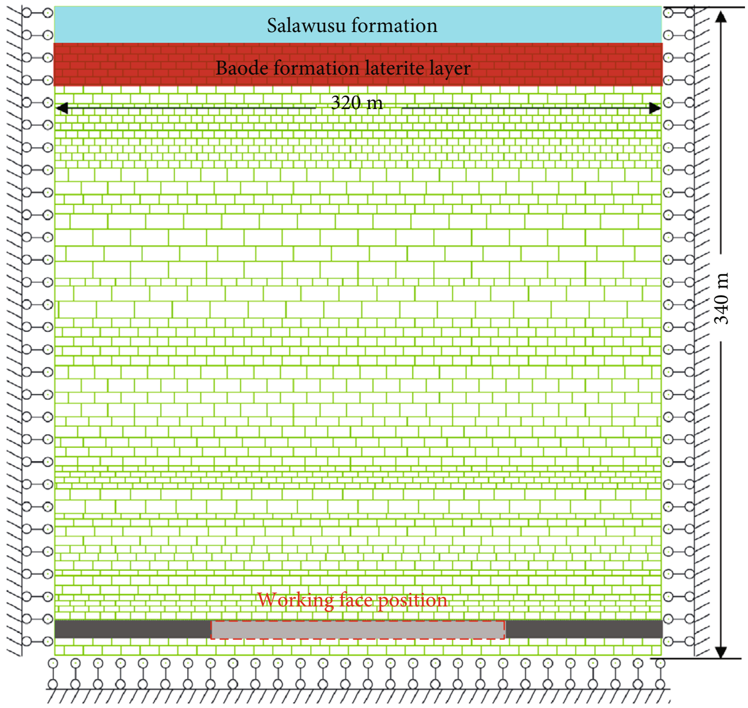


Figure 5: Geometric model of numerical simulation.

of the water-conducting fractured zone in the process of extracting the 2^{-2} coal seam 2-2 in the Guojiatan coal mine by using the layered-backfill-based slicing mining method, with the geometric model depicted in Figure 5. Under the condition of slicing mining with natural roof caving, the development height of the water-conducting fractured zone in the overburdened strata was simulated with a backfill ratio of 60%, 70%, 80%, and 90% [37–39].

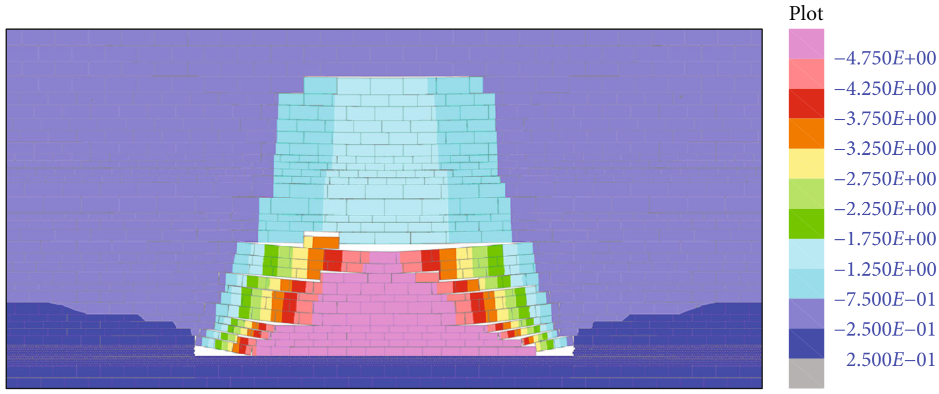
3.3.2. Analysis of Overburden Structure. The mining heights of the upper and lower layer of the 2^{-2} coal seam are 5.0 m and 3.0 m, with 1.15 m of coal being reserved at the top. The characteristics of the overburden structure after slicing mining the upper and lower layer were similar. Therefore, to investigate the impact of different backfill ratios on overburden structure, the overburden migration characteristics and displacement contours after slicing mining the upper layer are analyzed and shown in Figure 6.

As shown in Figure 6, in the process of mining the upper-layered coal, different mining method and backfill ratio have a significant impact on the migration characteristics of the overburdened strata. Regarding the scenario of the caving mining method, violent strata movement and evident caving zone could be observed, while no evident caving zone was formed with the backfilling mining method. Noticeable layer separation occurred for the scenario of the backfill ratio of 60% and 70%, with the maximum separation distance of 1.09 m and 0.64 m, whilst the overburden displacement was extremely small, and the strata only bent without evident overburden fracture for the case where a backfill ratio of 80% and 90% was employed.

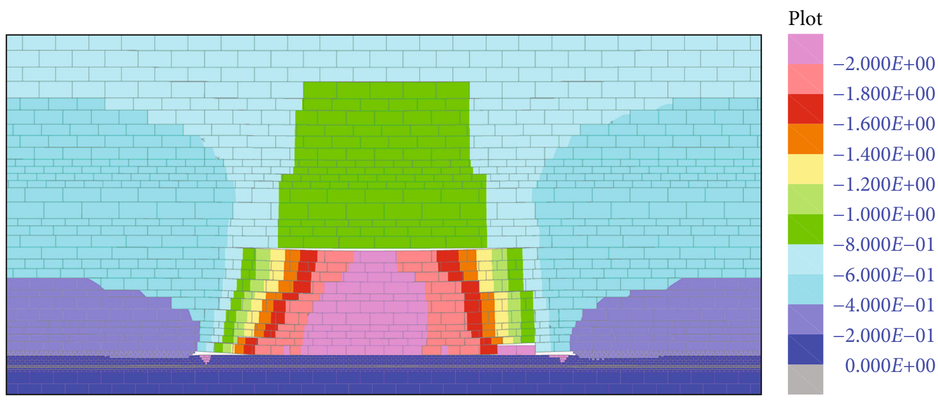
The displacement of strata above the working face showed a nonuniform trend, with a high value in the centre of the goaf and a lower value on the periphery. With the increase in the backfill ratio, the nonuniformity of the overburden displacement distribution weakened. This is because the collapse in the centre of the goaf area is relatively intense for the caving mining, and the displacement of the overburden strata is large, which is approximately equal to the mining height. But due to the existence of the arc-shaped triangular structure in the vicinity of the coal pillar, the overburden displacement is relatively small, resulting in apparent nonuniform displacement distribution of the overburden strata. However, the equivalent mining height is reduced for the backfill mining, which gradually weakens the movement of the overlying strata and decreases the displacement in the centre of the goaf area. Therefore, the nonuniformity of the overburden displacement distribution is weakened.

3.3.3. Development Characteristics of Water-Conducting Fracture. The mining height of the upper-layered coal seam is 5.0 m, and the evolution characteristics of water-conducting fractures for each mining scenario are shown in Figure 7.

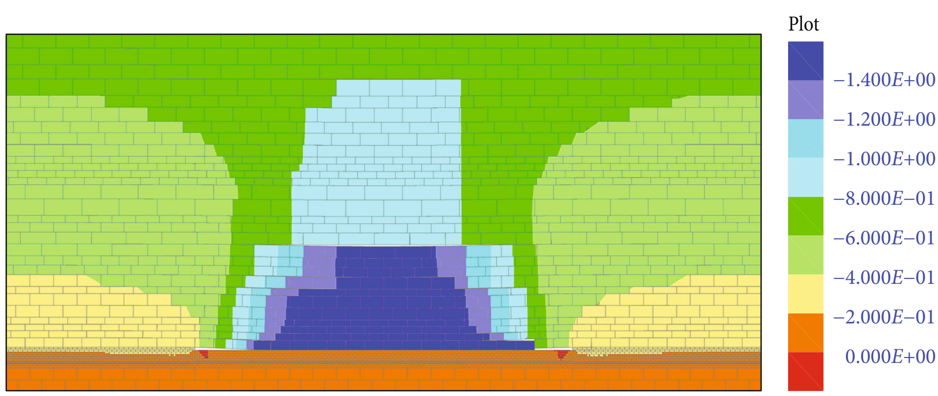
As illustrated in Figure 7, backfilling mining can significantly reduce the development height of the water-conducting fractured zone. As the backfill ratio rises, the height of the water-conducting fractured zone decreases gradually. Specifically, the development height of the water-conducting fractured zone is 124 m for the caving mining method, while it is 46 m, 45 m, 25 m, and 10 m for the backfilling mining with a backfill ratio of 60%, 70%, 80%, and 90%. In addition, the water-conducting fractures develop plentifully above both sides of the longwall goaf but underdevelop in the centre of the goaf area. This is because an arc-shaped triangular structure exists on both



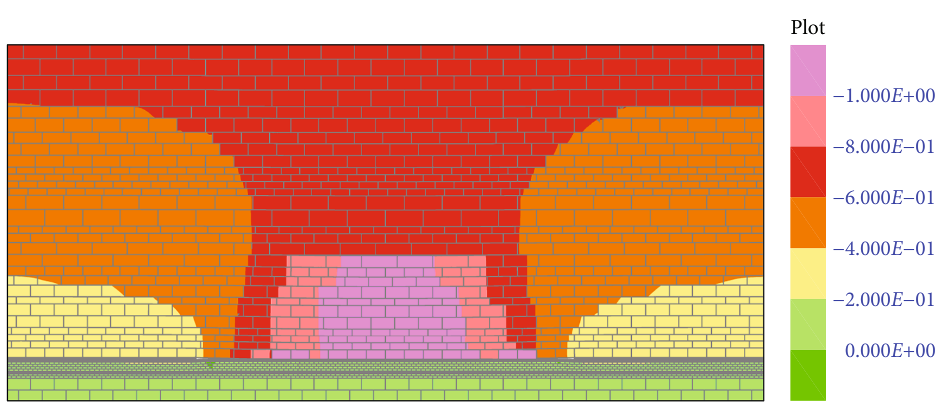
(a) Caving mining



(b) 60% backfilled ratio

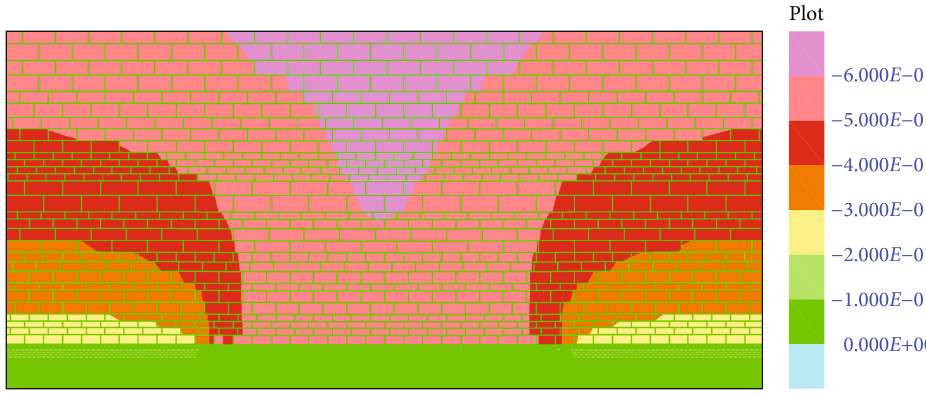


(c) 70% backfilled ratio



(d) 80% backfilled ratio

Figure 6: Continued.



(e) 90% backfilled ratio

FIGURE 6: Migration characteristics and displacement contours of the overburden structure under different mining scenarios.

sides of the longwall goaf, and the rock block rotates after fracturing, which leads to more developed fractures on both sides of the goaf area. Conversely, the central part of the roof above the mined-out seam sinks as a whole, and some transverse cracks and fractures are closed as a result of the consolidation effect.

The mining thickness of the lower-layered coal seam is 3.0 m, and the evolution characteristics of the water-conducting fractures for the lower layer demonstrate a similar trend to the upper layer. Specific to the lower layer mining, the development height of the water-conducting fractured zone is 144 m for the caving mining, whereas it is 58 m, 46 m, 30 m, and 12 m for backfilling mining with a backfill ratio of 60%, 70%, 80%, and 90%, respectively, as illustrated in Figure 8.

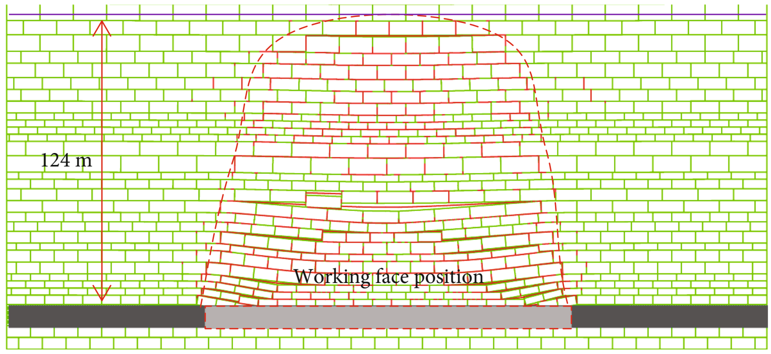
4. Detailed Analysis of the Water-Conducting Fractures and Determination of Key Parameters for Backfilling Mining

4.1. Detailed Analysis of the Evolution Characteristics of the Water-Conducting Fractures. The developing height of the water-conducting fractured zone under different mining conditions is obtained using theoretical calculation, measured analogy, and numerical simulation, as shown in Figure 9.

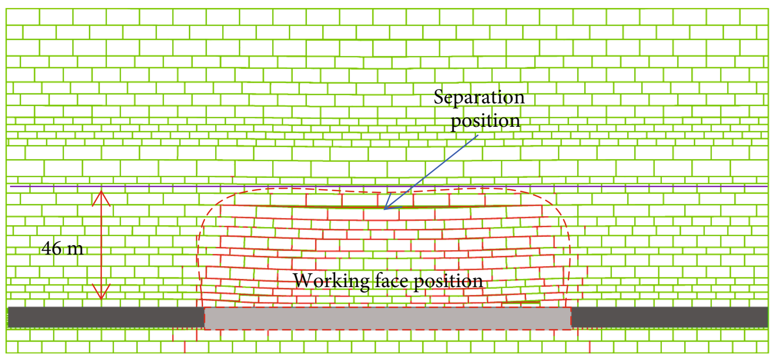
Detailed analysis of the results illustrated in Figure 9 indicated that the developing height of the water-conducting fractured zone obtained by the measured analogy is always higher than the prediction value, regardless of the mining conditions. From the perspective of conservativeness, the developing height of the water-conducting fractured zone obtained by the measured analogy results is used as the final height. The maximum developing height of the water-conducting fractured zone is 220.0 m (developing to the Anding Formation) for the caving mining, while it is 88.0 m (developing to the Zhiluo Formation), 66.0 m (developing to the Zhiluo Formation), 44.0 m (developing to the Zhiluo Formation), and 22.0 m (developing to Yan'an Formation) for backfilling mining with a backfill ratio of 60%, 70%, 80%, and 90%.

4.2. Determination of the Key Parameters for Backfilling and Relevant Performance. According to the reports titled "Overall Plan for the Phase III Planning Area of the Yushen Mining Area of the Jurassic Coalfield in Northern Shaanxi Province," the Zhiluo Formation and the Yan'an Formation are both characterized by continental deposits, and the distribution characteristics of sandstone are mainly controlled by sedimentary facies. The Zhiluo Formation and the Yan'an Formation are mainly composed of mudstone and siltstone, with a small portion of sandstone. The underground water is mainly reserved in the sandstone section. The thickness of the Zhiluo Formation is 0-297.62 m, with an average of 97.7 m. The water depth of cover is 0.69-111.60 m. When the water depth of cover is 18.09-109.70 m, the water emission rate is 0.05-4.24 L/s. The unit water emission is 0.001-0.239 L/s·m, with an average of 0.036 L/s·m. The permeability coefficient is 0.00281~0.35469 m/d, with an average of 0.079 m/d. The Zhiluo group has weak water-rich. The thickness of the Yan'an Formation is 59-329.86 m, with an average of 216.65 m. The unit water emission is 0.0001-0.053 L/s·m, with an average of 0.006 L/s·m. The permeability coefficient is 0.0003-0.140 m/d. The Yan'an Formation shows weak water-bearing characteristics.

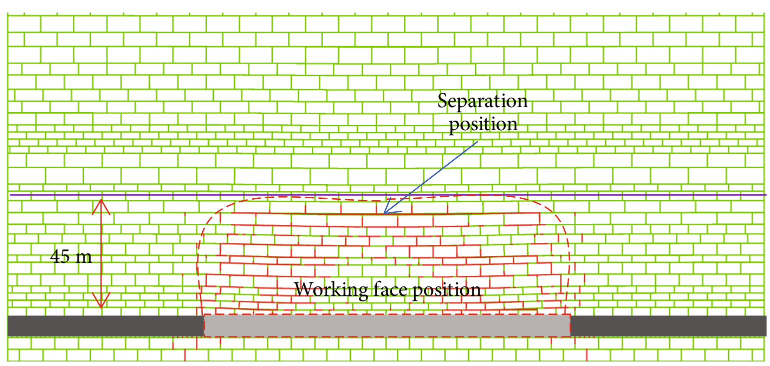
The field measured data at the Jinjitan coal mine indicated that the permeability coefficient of Zhiluo Formation in the bending deformation zone above the goaf area is 0.0025~0.0170 m/d, with an average of 0.0080 m/d. There is no significant difference in the permeability of the Zhiluo Formation in the bending deformation zone. As for the Zhiluo Formation located in the water-conducting fractured zone, its permeability coefficient increases sharply. The average permeability coefficient is 0.0780 m/d within the measurable range of the water pressure test. Compared with the natural status, the permeability coefficient of the Zhiluo Formation increases by one order of magnitude as a result of mining, indicating that the permeability of the Zhiluo Formation in the water-conducting fractured zone is seriously



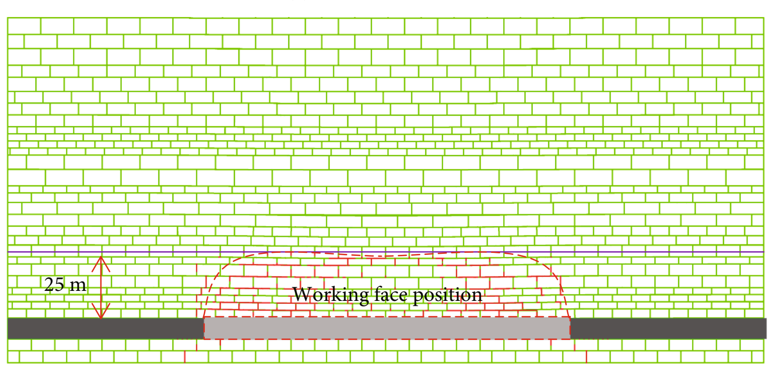
(a) Caving mining



(b) 60% backfilled ratio

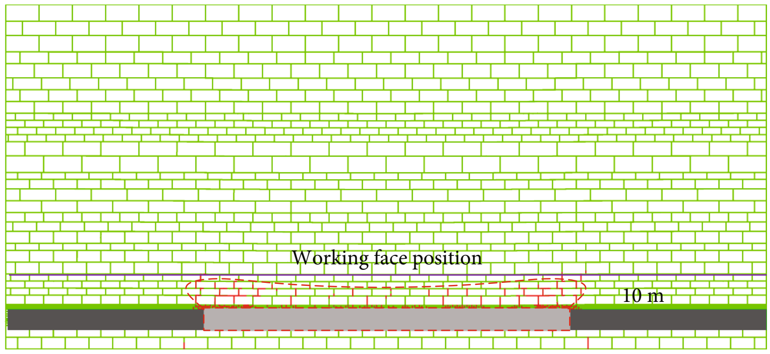


(c) 70% backfilled ratio



(d) 80% backfilled ratio

Figure 7: Continued.



(e) 90% backfilled ratio

Figure 7: Evolution characteristics of water-conducting fractures in the overburden under different mining conditions.

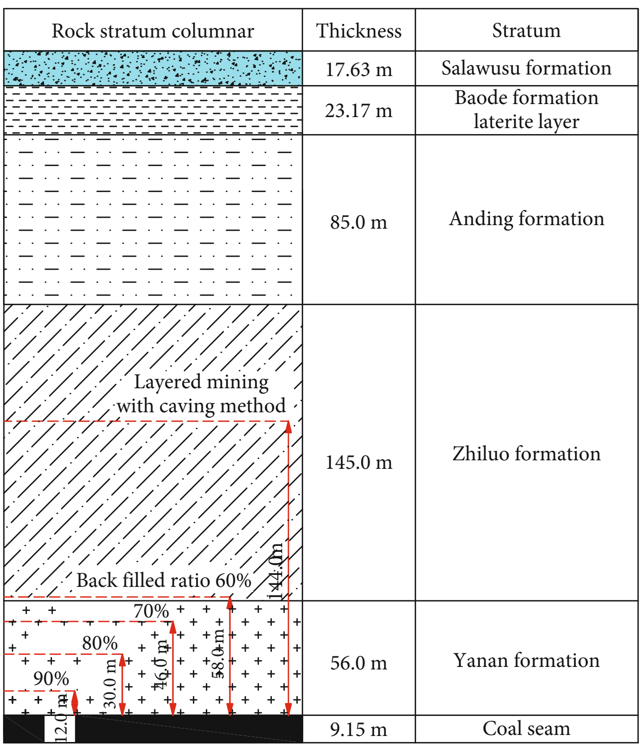


Figure 8: Simulation results of the water-conducting fracture height under different mining conditions.

affected by mining activities [40]. The above data show that the water-bearing characteristics of the Zhiluo Formation are more robust than that of the Yan'an Formation, and the water-conducting fractured zone develops into the Zhiluo Formation, leading to a sharp increase in the permeability coefficient of the Zhiluo Formation.

In order to further reduce the developing height of the water-conducting fractures zone, the backfill mining method is applied to enable the water-conducting fractured zone solely to develop into the fifth part of the Yan'an Formation. As a result, the Zhiluo Formation is transformed from a direct water-filled aquifer to an indirect water-filled aquifer, and the impact of the fracture zone on disturbing the water-bearing aquifer and the thickness of the direct aquifer is minimized, which assists in reducing the water emission.

The detailed analysis of the evolution characteristics of the water-conducting fractures indicated that a minimum backfill ratio of 80% is required to ensure that the water-conducting fractured zone only develops to the Yan'an Formation without crossing the Zhiluo Formation.

Combined with the analysis of the boreholes in the vicinity of the first mining face, the distance between the top of the water-conducting fractured zone and the floor of the Zhiluo group is shown in Figure 10.

Figure 10 shows that after the slicing mining is finished with a backfilled ratio of 80%, the distribution of the distance between the top of the water-conducting fractured zone and the floor of the Zhiluo Formation presents a trend of "thick in the west and thin in the east." The Zhiluo Formation is transformed into an indirect water-filled aquifer, and the mine water emission is further reduced.

When the slicing mining method is employed with the roof naturally caving, the maximum developing height of the water-conducting fractured zone is approximately 220.0 m. The water emission rate in the west of the testing area is 334.95 m^3/h based on the big well method [41–43]. When the slicing mining method is adopted, and the goaf area is backfilled with a backfill ratio of 80%, the developing height of the water-conducting fractured zone is only 44.0 m. The water emission rate in the west of the testing area is 60.60 m^3/h. It is noted that compared to the caving method, the water emission rate in the west of the testing area for the backfilling method is reduced by 290.95 m^3/h, with a reduction ratio of 86.86%, demonstrating that a noticeable reduction in the water emission rate is obtained.

According to the isotopic testing results of the mine water in the vicinity of the operating coal mines, the proportion of the mine water sourced from each coal mine is calculated, as listed in Table 2 [44, 45].

Based on the rules of the maximum proportion of 25%, the shallow water overflow is reduced by 72.74 m^3/h compared to the scene prior to the backfill-based slicing mining. It is estimated that the shallow water loss can be reduced by 637200 m^3 annually, which is equivalent to 1.74% of the actual water supply of the centralized water source in Yulin

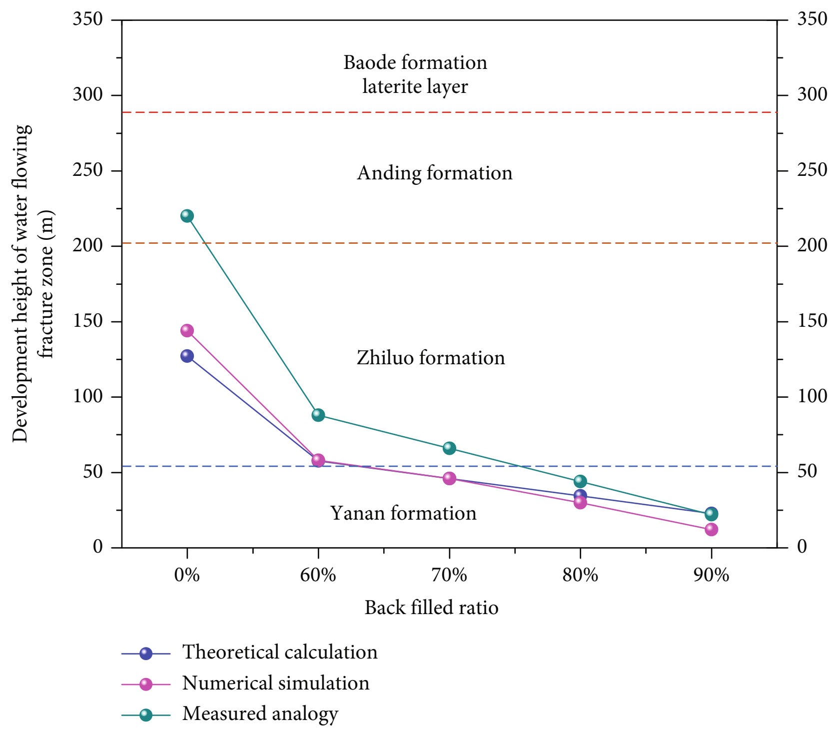


FIGURE 9: Detailed analysis of the height of water-conducting fractured zone under different mining conditions.

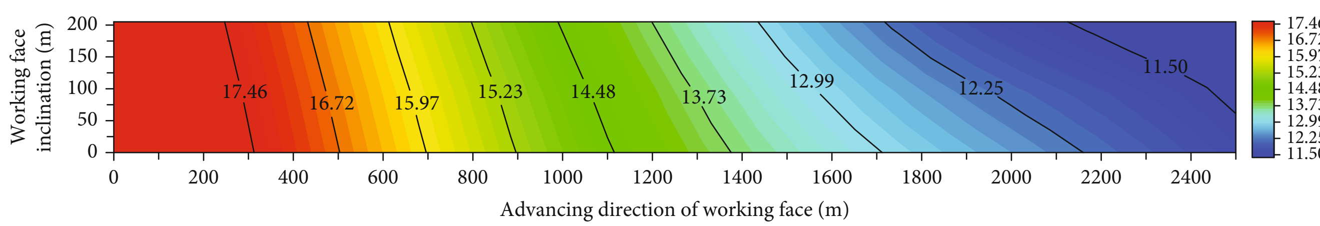


FIGURE 10: The distance between the top of the water-conducting fractured zone and the floor of the Zhiluo group.

TABLE 2: Proportion of mine water sourced from the surrounding operating coal mines.

Coal mine			Isotopic characteristics		Proportion of shallow water (%)
Name	Overburden combination	Depth (m)	$\delta^{18}O$	δD	
Jin Jitan	$Q + N + J_2z + J_2y, Q + N + J_2a + J_2z + J_2y$	229.6~262.1	-10.8	-81.5	7.0~25.0
Caojiatan	$Q + N + J_2z + J_2y, Q + N + J_2a + J_2z + J_2y$	255~338	-10.8	-81.9	7.0~25.0
Xiaobaodang no.1	$Q + N + J_2a + J_2z + J_2y$	296.7~367.73	-10.8	-81.2	7.0~25.0

city. It is to be noted that the loss of surface water resources that play an indispensable role in daily life can be significantly reduced.

5. Design of the Layered Backfilling Mining

5.1. Layout Parameters of the Working Face. The West Wing of panel 201 is designed close to the shaft for the purpose of easily forming an integrated mining system, and the length of the working face is short, which is more conducive to the layout of the backfilling face. Therefore, the west of panel 201 is designed as the backfilling area at the early stage, and the first backfilling face CT20102 is situated in the south of panel 201, as shown in Figure 11.

CT20102 backfilling working face is 160 m long with an advancing distance of 2480 m. The minimum backfilled ratio is 80%, and 6 cutting web is operated per day, resulting in a mining capacity of 1.44 Mt/a.

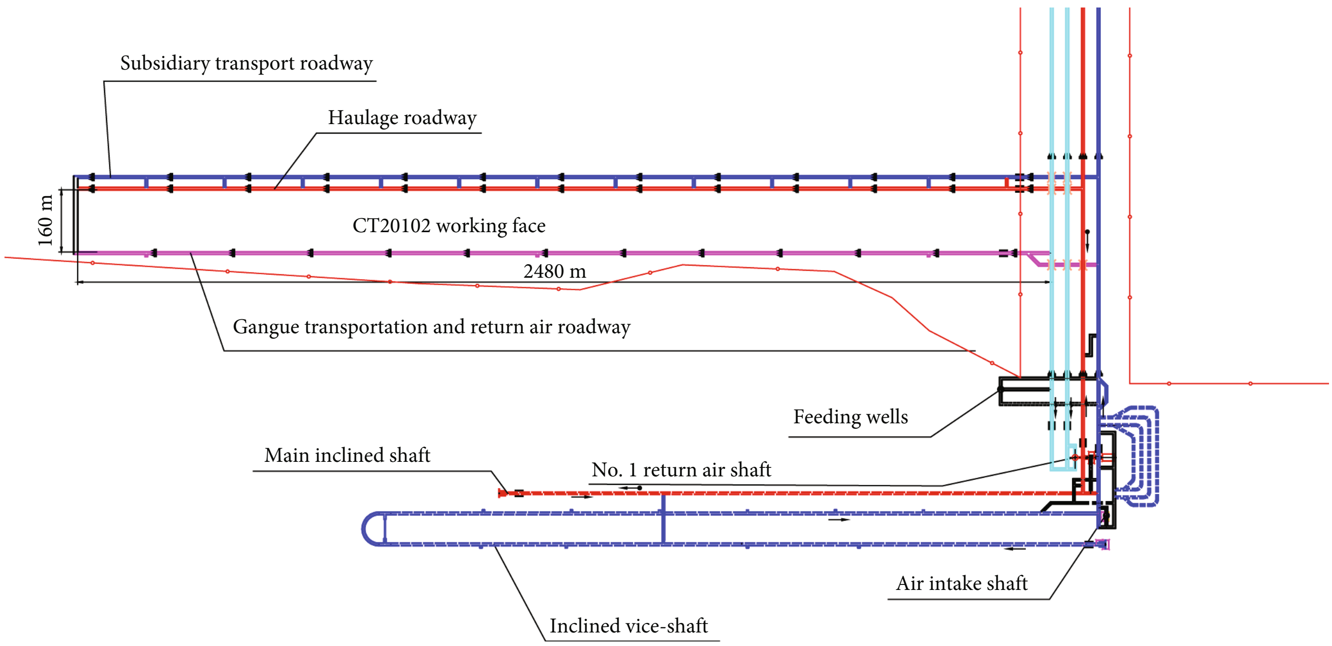


Figure 11: Layout of backfilling working face.

5.2. Efficient Parallel Process of Coal Mining and Backfilling. Backfilling process: after the shearer cuts the coal and the hydraulic support advances, the insert plate of the porous bottom discharge scraper conveyor is opened to discharge the gangue.

The specific operation steps are:

(1) First, open 10~18 discharge holes at the head of the perforated bottom discharge conveyor close to the head. Every 3 sets of brackets are set up in a group, and 3 groups are designed to discharge waste at the same time

(2) When the waste discharged by the discharged hole reaches a certain height, the full mining height tamping system jack at the rear of the bracket where the discharge hole is located operates immediately to push the tamping plate to compact the unloaded filling material

(3) After the compaction is completed, close the 10~12 plugs, and open the 7~9 discharge holes

(4) When the 13th to 15th discharge holes are unloaded to a certain height, immediately start the tamping system jack at the rear of the bracket where the discharge hole is located to push the tamping plate

(5) After the compaction is completed, close the 13~15 plugs, and open the 4~6 discharge holes

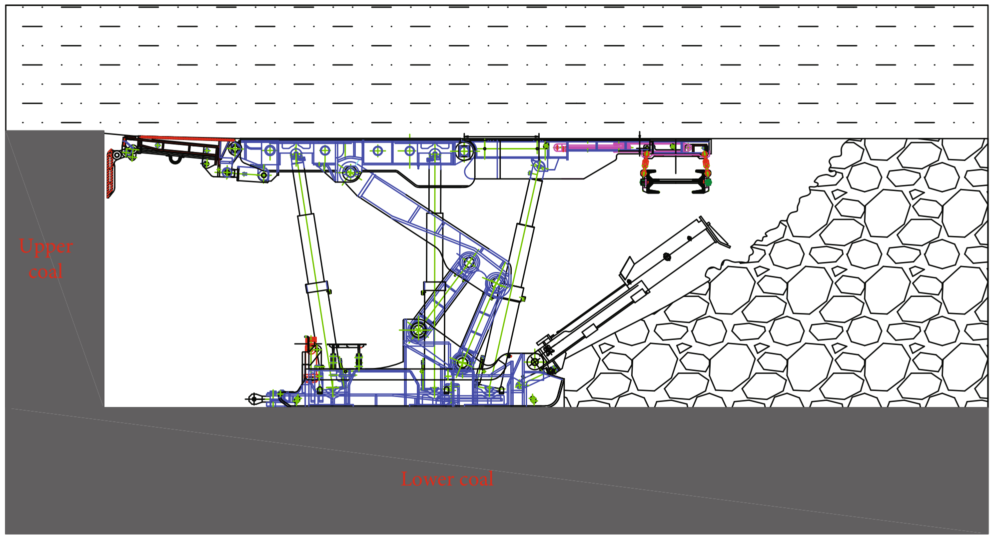
Repeat the above steps to perform backfilling from the tailgate towards the maingate using the same method. The second cycle of backfilling operation starts until all the discharged operations are completed for all backfilling support on the working face, as shown in Figure 12.

5.3. Hydrological Monitoring and Feedback Adjustment of the Backfill Ratio

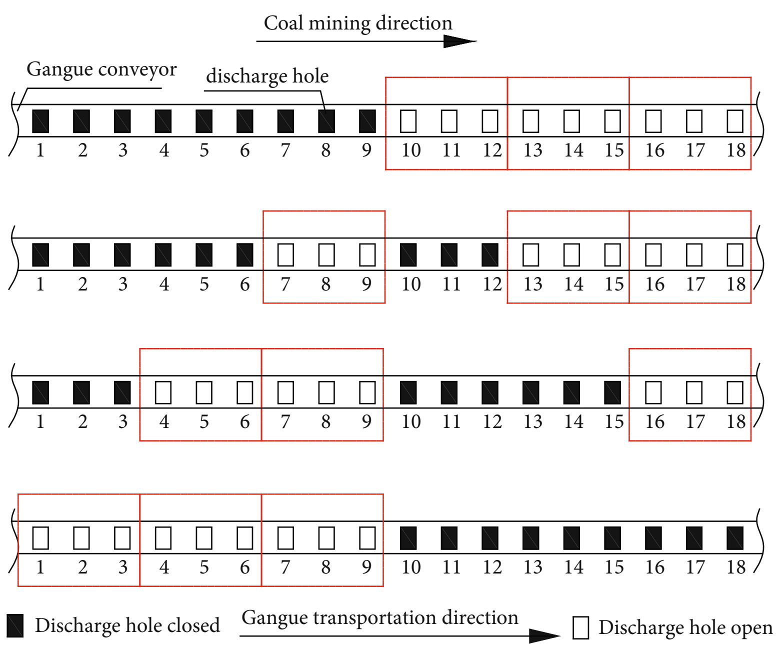
5.3.1. Surface Hydrological Monitoring System. The surface observation system is set up in the Guojiatan minefield, which is mainly used to continuously monitor the water level of the Zhiluo Formation aquifer and Salawusu Formation aquifer. The automatic observation mode of self-recording water level gauge is adopted to know the change in aquifer water levels before and after coal mining. A total of 8 hydrological observation holes are designed, including 5 observation holes for the aquifer of Salawusu Formation and 3 observation holes for the aquifer of Zhiluo Formation. The layout is shown in Figure 13.

5.3.2. Underground Hydrological Monitoring System. The underground hydrological monitoring system mainly monitors the water emission from the goaf, the total water volume within the pipeline, the total water volume of the open channels, and the water pressure of the underground roof boreholes. The water levels are monitored automatically, with an observation frequency of 10 min. The water samples in the boreholes drilled in the Yan'an Formation and the mine water (mixed water) are collected routinely (15 days) and analyzed, including K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO^{3-}, SO_4^{2-}, hardness, mineralization, pH value, and other hydrochemical indexes. In addition, the portion of the shallow water to the total water is calculated by analyzing the content of the δD (deuterium) and δ^{18}O (oxygen isotope) in the sampled water and combining the condition of the water from the surface boreholes.

5.3.3. Monitoring Scheme of Height of Water-Conducting Fractured Zone. According to the movement law of overburden, in order to ensure the accuracy of observation results of



(a) Compaction process of single-filling support for gangue discharge



(b) Multisupport synergistic filling process

FIGURE 12: Coal mining filling parallel and group filling process.

water-conducting fractured zone, the observation point is located 200 m behind the working face. Two observation holes for water diversion fissure zone are constructed from the haulage roadway to the goaf of the working face, and a comparison hole is constructed to the solid coal side. The development height of the water-conducting fractured zone in the working face is determined by comparing the water injection leakage of the comparison hole and the observation hole.

5.3.4. Feedback Adjustment System of the Backfill Ratio. The mine water emission rate and the water infiltration from the Salawusu Formation and the height of water-conducting fractured zone are the key parameters that should be paid attention to. Therefore, it is significant to record the changes in mine water emission, overflow, and the height of water-conducting fractured zone during the mining process while carrying out water conservation mining. The backfilling ratio of the solid filling face is adjusted based on the monitoring results to ensure the water protection effect, as shown in Figure 14. The experience is summarized to provide guidance for water protection mining in this area.

6. Conclusions

(1) This paper elaborates on the connotation and necessity of water protection mining in the Guojiatan coal mine from the perspective of generalized water

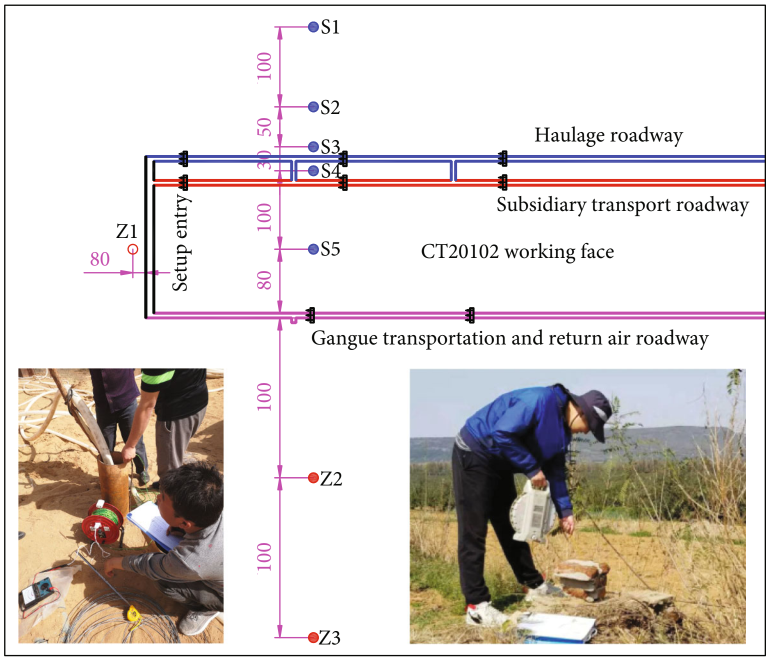


FIGURE 13: Layout of the hydrological monitoring system.

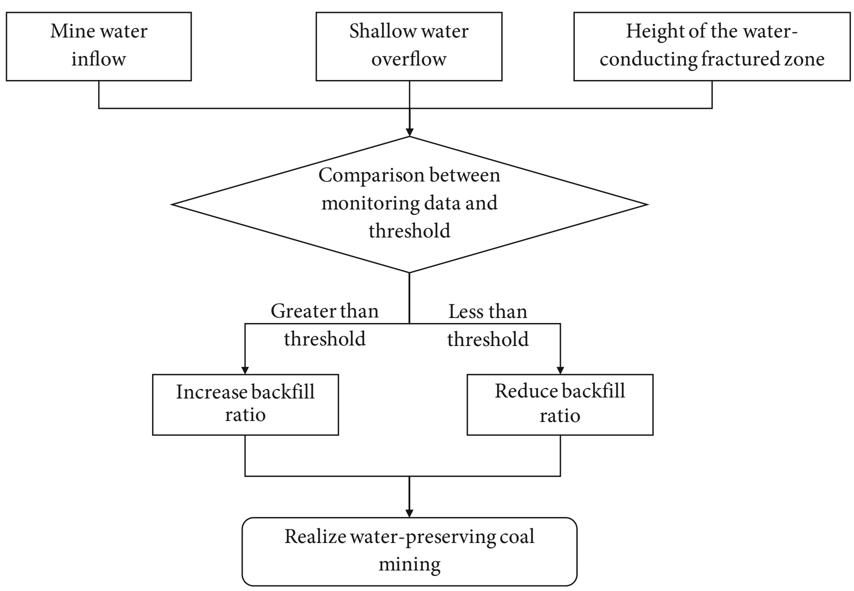


FIGURE 14: Feedback adjustment system of the backfill ratio.

protection mining. While protecting the stability of the water-blocking strata underlying the aquifer, it is of importance to minimize the water emission rate and coordinate coal mining and water protection, which plays a significant role in reducing the loss of the Quaternary shallow water resources and maintaining the water supply of the Hongshixia water source

(2) In combination with the theoretical calculation, measured analogy and numerical simulation, is calculated to be 220.0 m (developed to the Anding Formation) when the slicing mining method is adopted with the roof naturally caving. However, the maximum developing height of the water-conducting fractured zone is 88.0 m (developing to the Zhiluo Formation), 66.0 m (developing to the Zhiluo Formation), 44.0 m (developing to the Zhiluo Formation), and 22.0 m (developing to Yan'an Formation) for backfilling mining with a backfill ratio of 60%, 7%, 80%, and 90%

(3) Based on the detailed analysis of the developing height of the water-conducting fractured zone, the

minimum backfilled ratio of 80% is required to ensure that the water-conducting fractured zone only develops to the Yan'an Formation without crossing the Zhiluo Formation. The water emission rate in the west of the testing area is reduced from 334.95 m^3/h to 60.60 m^3/h, with a reduction ratio of 86.86%, illustrating an effective water emission reduction performance

(4) Compared to the status prior to the backfill mining, the shallow water overflow is reduced by 72.74 m^3/h, and the shallow water loss can be reduced by 637200 m^3 per year which is equivalent to 1.74% of the actual water supply of centralized water sources in Yulin city. It is to be noted that the loss of surface water resources that play an indispensable role in daily life can be significantly reduced

(5) According to the specific layout of the Guojiatan, the designed backfilling face is 160 m long with an advancing distance of 2400 m. In addition, the high-efficiency parallel process of mining and backfilling is provided, and the monitoring scheme of mine water inflow and overflow is designed, which allows the backfill ratio of the backfilling face to be adjusted according to the hydrological monitoring results and improves the water protection performance during the mining process

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflict interest.

Acknowledgments

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