

Article

Feasibility Study on the Construction of Underground Reservoirs in Coal Goaf—A Case Study from Buertai Coal Mine, China

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Abstract: The construction of underground reservoirs in coal goaf is a new technology aimed to realize the sustainable development of coal mining-water storage-surface ecology in arid areas of northwest China. The key to the feasibility of this technology is that underground coal mining cannot affect the near-surface aquifer, and the amount of water entering the underground reservoir must meet the needs of the coal mine. Taking Buertai Coal Mine, one of the largest underground coal mines in the world, as an example, this article used similar simulation, numerical simulation and in-situ test methods to study the height of the water-conducting fracture zone of overlying strata and water inflow of underground reservoirs. The results show that, under the repeated mining of the 22- and 42-coal seams, the maximum height of the water-conducting fracture zone is 178 m, and the distance between the near-surface aquifer and the 42 coal is about 240 m, so the mining has little effect on the near-surface aquifer. During the mining period of the 22-coal seam, the groundwater of the Zhidan and Zhiluo Formations was mainly discharged vertically, while the groundwater of the Yanan Formation was mainly a horizontal flow during the period of the 42-coal mining. In this way, the total water inflow of Buertai Coal Mine reaches 500 m³/h, which not only meets the needs of the mine, but also, the rest of the water can irrigate about 98 hectares of farmland nearby. Underground reservoirs in coal goaf could achieve sustainable development of coal mining, groundwater storage and surface ecology in semi-arid areas.

Keywords: underground reservoir; coal goaf; feasibility; water inflow; water-conducting fracture zone



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1. Introduction

Water is a key basic condition for sustainable human development [1,2]. China is one of the 13 water-scarce countries in the world [3,4]. In 2020, China's per capita water resources were 2214 m³, only one-fourth of the world average [5]. In particular, provinces such as Shanxi, Shaanxi, Inner Mongolia, Gansu and Ningxia in northwest China are located in arid and semi-arid areas with rainfall of 0–600 mm. They are extremely scarce in water resources, with the total water resources accounting for only 3.9% of the country's total [6–9]. In sharp contrast to the shortage of water resources, coal production in the above-mentioned areas accounts for about 70% of the country's coal production and is an important source of income for local people [10]. However, approximately 4.2 billion tons of groundwater is destroyed every year due to coal mining [11,12], further damaging the already fragile ecological environment in the northwest region.

The underground reservoir in coal goaf is a new technology to solve the above coal–water contradiction [13]. This technology uses the high porosity space formed in the coal goaf to store water, uses the water-conducting cracks in the overlying rock to guide part of the underground water into the goaf, and uses the adsorption of rocks to adsorb harmful impurities to form a natural filtration purifier. At the same time, it controls the

development of water-conducting fissures to protect near-surface water and achieve the purpose of protecting surface ecology [14]. However, the construction of underground reservoirs has high requirements on local engineering geological conditions. Once the height of the water-conducting fracture zone is too high, the near-surface aquifer may be damaged, and cracked claystones are particularly susceptible to water in water hazard conditions [15]. In addition, if the water inflow is too small, the reservoir may have no water available. Therefore, the height of the water-conducting fracture zone and the water inflow into the underground reservoir are the core factors that determine the construction of the underground reservoir in the goaf area.

At present, scholars often use comprehensive methods to determine the height of the water-conducting fracture zone. He et al. [16], Jiang et al. [17] and Wang et al. [18] believed that the thickness of the coal seam and the position of the key stratum are the key factors affecting the height of the water-conducting fracture. The thickness of the coal seam determines the lower limit of the height of the water-conducting fracture, and the first key stratum above the fracture determines its upper limit. On this basis, the expression of the height of the water-flowing fractured zone under the influence of the key stratum is established, and the above results are verified by the change of the water level of the borehole, the change of the leakage of the flushing fluid and the peeping of the borehole. Li et al. [19], Chen et al. [20] and Wu et al. [21] took the long-wall mining face of a coal mine as the research object, analyzed the development height of water-conducting fracture zones through empirical calculation formula, and combined FLAC 3D numerical simulation, a water-injection leakage detection method and a borehole TV-imaging method to obtain the ratio of the height of mining overburden failure zone to the thickness of coal seam. Han et al. [22], Li et al. [23] and Lei et al. [24] used the distributed optical-fiber sensing technology to monitor the strain of the optical fiber in the borehole in real time during the advancing process of the working face, so as to judge the deformation and fracture of the overburden rock under the mining stress, and then determine the development height of the water-conducting fracture. Lu et al. [25], Mai et al. [26], Wang et al. [27] and Zhang et al. [28] used discrete element numerical simulation and combined it with in-situ measured data to obtain a triangular shape of the envelope of the water-conducting fracture zone of weakly cemented overburden. Moreover, when the weakly cemented overburden is thick, it can have a significant control effect on the development morphology and height of the water-conducting fracture zone. On this basis, a prediction model for the development height of the overburden water-conducting fracture zone is established. In addition, numerical simulation is one of the important methods to determine the water inflow in coal mine goaf. Liu et al. [29] and Zhang et al. [30] used numerical simulation and combined it with a borehole peeping method to find that the height of the water-conducting fracture zone of mining overburden rock in shallow coal seam presents an extremely slow gradually expanding rapid development-increasing rate-decreasing development process. With the influence of mining, the amount of aquifer water is released intermittently, and the water inflow in the goaf increases and decreases alternately and shows a downward trend as a whole. Wu et al. [31] and Hua et al. [32], taking the loss of water resources in the Quaternary aquifer caused by coal mining as the engineering background, through hydrogeological drilling, concluded that the coal mining subsidence pit is the main reason for the loss of near-surface water resources, and the leakage of near-surface water is calculated by the numerical simulation method. Zhai et al. [33] and Shi et al. [34] used GMS seepage software to predict the dynamic change of roof water inflow during coal mining by constructing a numerical model, which overcomes the limitation of static water inflow based on the analytical solution of 'large well method'.

The above conclusions are obtained based on the conditions of single-coal-seam mining or overlapping arrangement of multi-coal-seam working faces. However, a prominent feature of Buertai Coal Mine is the coexistence of overlapping and staggered arrangement working faces, which leads to an unclear development of mining fracture height and unclear water inflow, which are two key parameters for building underground reservoirs.

Therefore, this article focuses on the layout characteristics of working faces in Buertai Coal Mine, and carries out a series of numerical simulation, similar simulation and in-situ experiments to determine the height of the water-conducting fracture zone and the amount of water flowing into the underground reservoir. At the same time, the impact of coal mining on near-surface aquifers is analyzed to determine the feasibility of building underground reservoirs in Buertai Coal Mine.

2. Similar Simulation Experiments

2.1. Project Profile

Burtai Coal Mine is located in Ordos City, Inner Mongolia, at the intersection of the Loess Plateau and Mu Us Desert (Figure 1). The average annual precipitation is about 440 mm, and surface vegetation is sparse. At present, 22 coal and 42 coal are mainly mined in the coal mine, with average thicknesses of 4 m and 6.5 m, respectively, and mining depths of 280 m and 350 m, respectively. Their dip angle is about $0\text{--}4^\circ$, belonging to nearly horizontal coal seams. Within the mining area (approximately 162 km^2), there are 223 faults with a general drop of $0\text{--}3\text{ m}$ (there are 193) and dip angles mostly between 58 and 65° . The working faces of the two coal seams have two basic working conditions: overlapping arrangement and staggered arrangement (Figure 2a). In addition, lithology and thickness of roof strata are shown in Figure 2b. Among them, the Quaternary aquifer, the Cretaceous Zhidan Group, the Jurassic Zhiluo Formation and the Jurassic Yanan Formation sandstone layer are the main aquifers of the coal seam. The mudstone layer under the Zhidan Group is the main water-proof layer. Under the influence of repeated mining of two layers of coal seams and coal pillars, water-conducting fissures in the overlying rock may be abnormally developed and the aquifer may be connected, causing an increase in water inflow from the underground reservoir in the goaf area. However, once the water-conducting fissure zone enters the near-surface aquifer (that is, Quaternary and Cretaceous aquifers), it can lead to near-surface water leakage and the deterioration of surface ecology. Therefore, the core of similar simulation experiments is to determine the height of the water-conducting fracture zone.

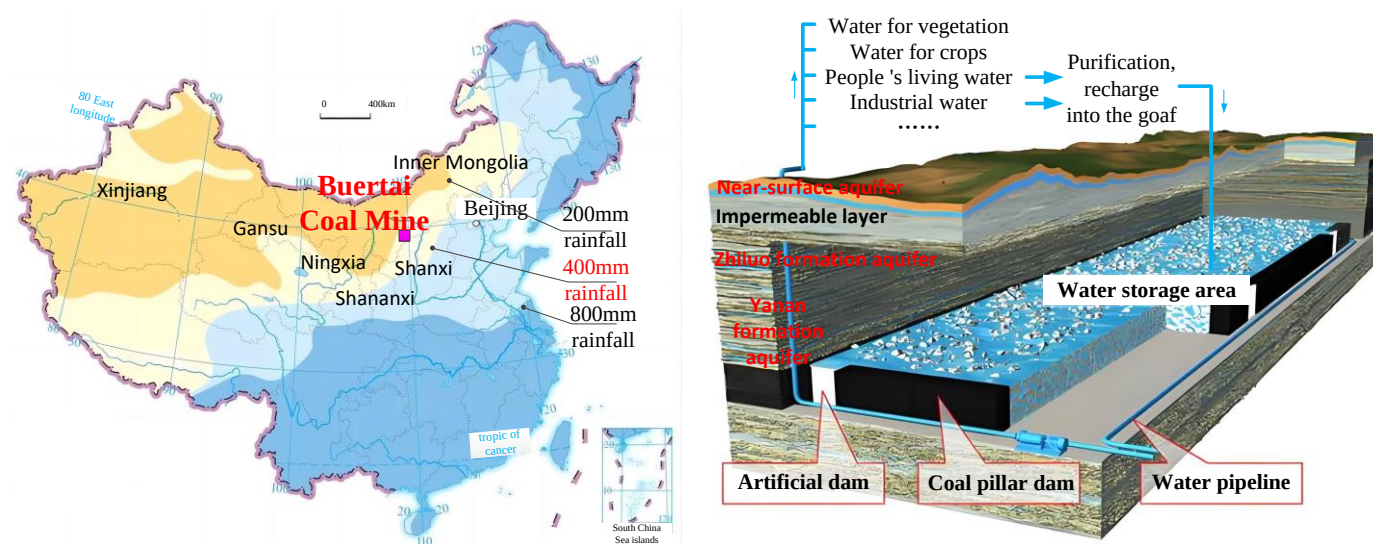


Figure 1. Position of Buertai Coal Mine and schematic diagram of underground reservoir of coal mine.

2.2. Similar Simulation Experiment Design

The 22201 and 42201 working faces and the 22205, 22206 and 42205 working faces of the Buertai mine were selected as the research areas (magenta box in Figure 2). Two simulation models were established, which were named Model 1 and Model 2, as shown in Figure 3a,b. The influence of multi-seam mining on the height of water-conducting fracture

zones of overlying strata was studied when the spacing between 22- and 42-coal pillars was 0 m and 177 m, respectively.

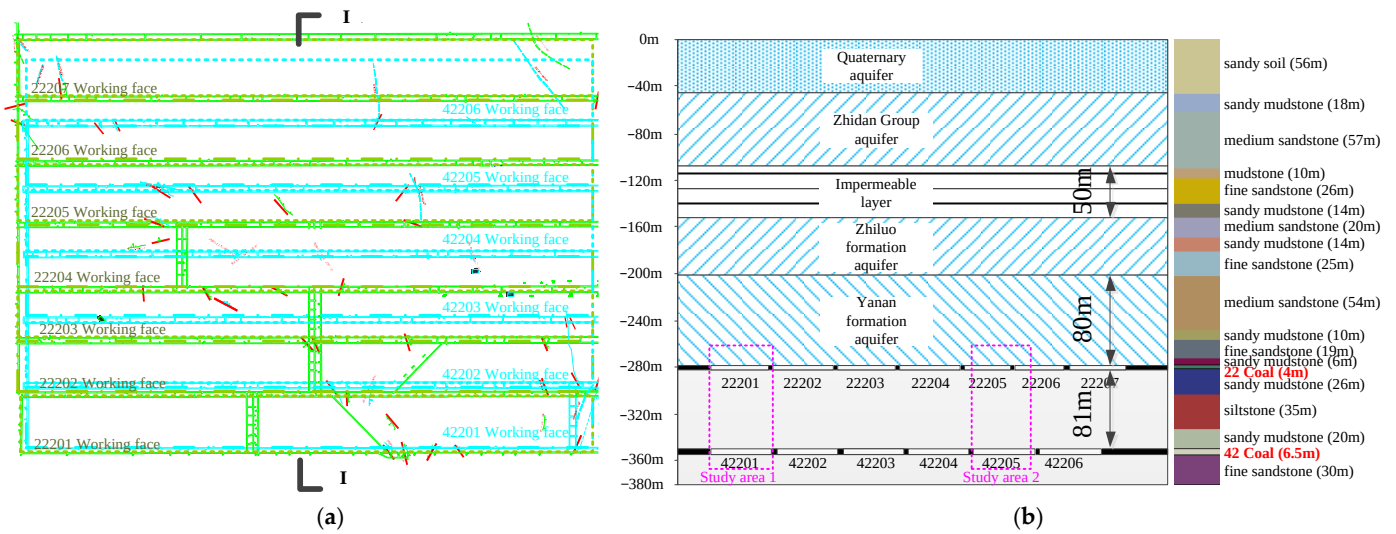


Figure 2. Layout of 22-coal and 42-coal working faces in Buertai Coal Mine. (a) 22-coal and 42-coal working-face layout plan; (b) I-I sectional view.

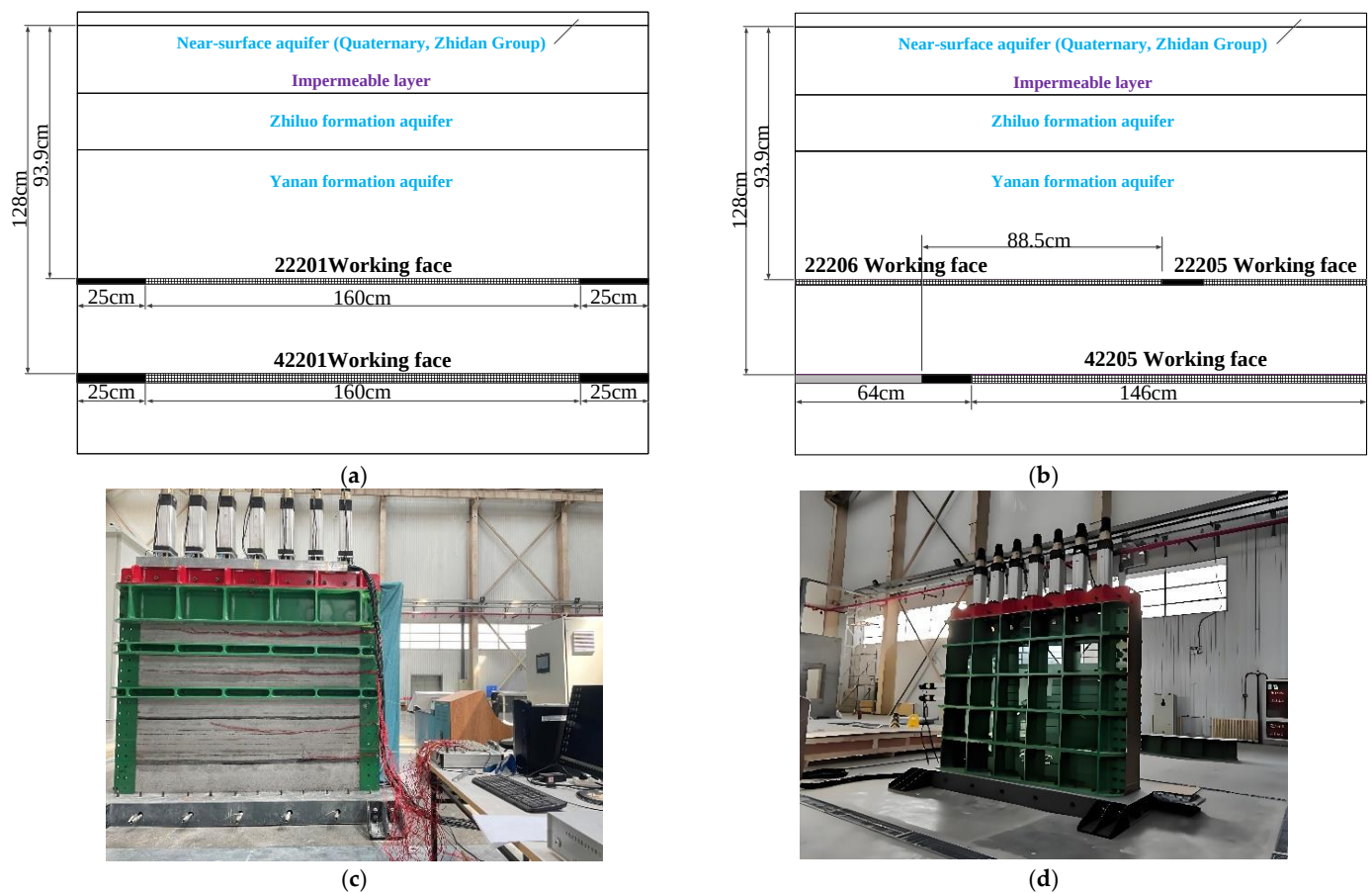


Figure 3. Similar simulation experiments. (a) Model 1; (b) Model 2; (c) similar model; (d) equipment.

Similarity ratio: Both models simulate a formation with a width of 420 m and a height of 360 m. Combined with the size of the “multi-coal seam mining coal mine underground reservoir simulation test platform” (Figure 3d), that is, length $\times$ height $\times$ thickness =

2100 mm × 1800 mm × 300 mm, the geometric similarity ratio is determined to be 1:200, the bulk density similarity ratio is 1:1, the stress ratio is 1:200 and the time similarity ratio is 1:14. The No. 42 coal seam in the study area has a mining depth of 350 m and a thickness of 6.5 m. The mining depth of the No. 22 coal seam is 280 m, and the thickness of the coal seam is 4 m. The distance between the two coal layers is about 81 m. In similar models, the floor of No. 42 coal is 15 cm thick, the coal seam is 3.2 cm thick, and the No. 22 coal seam is 2 cm thick. A total of 17 rock layers are laid from the floor upward. The model height is 180 cm.

Similar boundary conditions: The 64.5 m thick rock layer above the model is not laid, and its load is applied via a hydraulic strut and its value is 567 kg. The distribution of each rock layer in a similar model is shown in Figure 3, and the rock layer ratio and parameters are shown in Table 1.

Table 1. Material ratio of similar simulation tests.

Order	Lithology	Thickness/cm	Quartz Sand/kg	Barite/kg	Talc/kg	Cement/kg	Silicon Oil/kg	Water/kg	Compressive Strength/MPa	Tensile Strength/MPa
17	medium sandstone	3 2	46.6	13	22.8	1.4	1.7	9.2	0.17	0.01
16	mudstone	5	42	10	26	0.3	1.6	9.4	0.1	0.01
15	fine sandstone	7 6	232.7	65.1	113.4	8.8	8.4	46.2	0.23	0.016
14	sandy mudstone	7	63.4	17.2	29.2	0.7	2.2	12.2	0.37	0.026
13	medium sandstone	5 5.5	130.6	36.3	63.6	3.7	3.1	25.7	0.17	0.01
12	sandy mudstone	3.5 3.5	63.4	17.2	29.2	0.7	2.2	12.2	0.37	0.026
11	fine sandstone	4 4	174.1	48.7	84.3	6.6	6.3	34.6	0.23	0.016
10	medium sandstone	4.5 3 3 3 3 3 3 3 3	252.1	69.9	122.7	5.9	4.5	49.4	0.17	0.01
9	sandy mudstone	5	48	13	22	0.5	1.67	9.17	0.37	0.026
8	fine sandstone	9.5	87	24.3	42.1	3.3	3.1	17.3	0.23	0.016
7	sandy mudstone	3	28.8	7.81	13.25	0.3	1	5.55	0.37	0.026
6	No. 22 coal	2	16.3	4.4	7.8	0.2	0.6	3.1	0.11	0.01
5	sandy mudstone	3 5 5	105.7	28.6	50.5	1.8	3.7	20.3	0.37	0.026
4	siltstone	5.5 4 4 4	226	62.8	109.2	7.6	8	44.4	0.27	0.023
3	sandy mudstone	5 5	61.5	16.7	28.3	0.6	2.2	11.8	0.37	0.026
2	No. 42 coal	3.2	30.8	8.3	14.1	0.32	1.1	5.9	0.11	0.01
1	fine sandstone	15	252.7	68.5	120.6	4.4	8.8	48.6	0.37	0.026

According to the relevant literature [35], combined with the engineering geological characteristics of the Buertai mine, quartz sand, barite, talcum powder, cement, silicone

oil and mica powder were selected as similar materials. Their proportions are shown in Table 1.

Experimental steps:

- (1) Model laying: Weigh and stir similar materials separately as described in Table 1, then load them into the model layer by layer, and use a scraper to smooth and compact the materials. After laying one layer according to the designed stratum, sprinkle mica powder to isolate it from the next layer of rock layer, and gradually lay it out until it reaches the height of the model.
- (2) Apply vertical force: After the model is laid, the load is applied on the model top through the loading system.
- (3) Drying and force balance: Leave the model for 9 days to dry to achieve corresponding strength. At the same time, speckles were sprayed on the front of the model to prepare for further monitoring of cracks through the DIC digital speckle system.
- (4) Excavation measurement: According to the excavation position shown in Figure 3, excavate 3 cm each time with an interval of 5 min. During this period, the distribution of overlying rock fissures was observed.

2.3. Similar Simulation Results

(1) Model 1

The height of the fracture zone and the displacement of the overlying rock after mining in the 22201 and 42201 working faces are shown in Figure 4. DIC analysis and result visualization were realized by MultiDIC software.

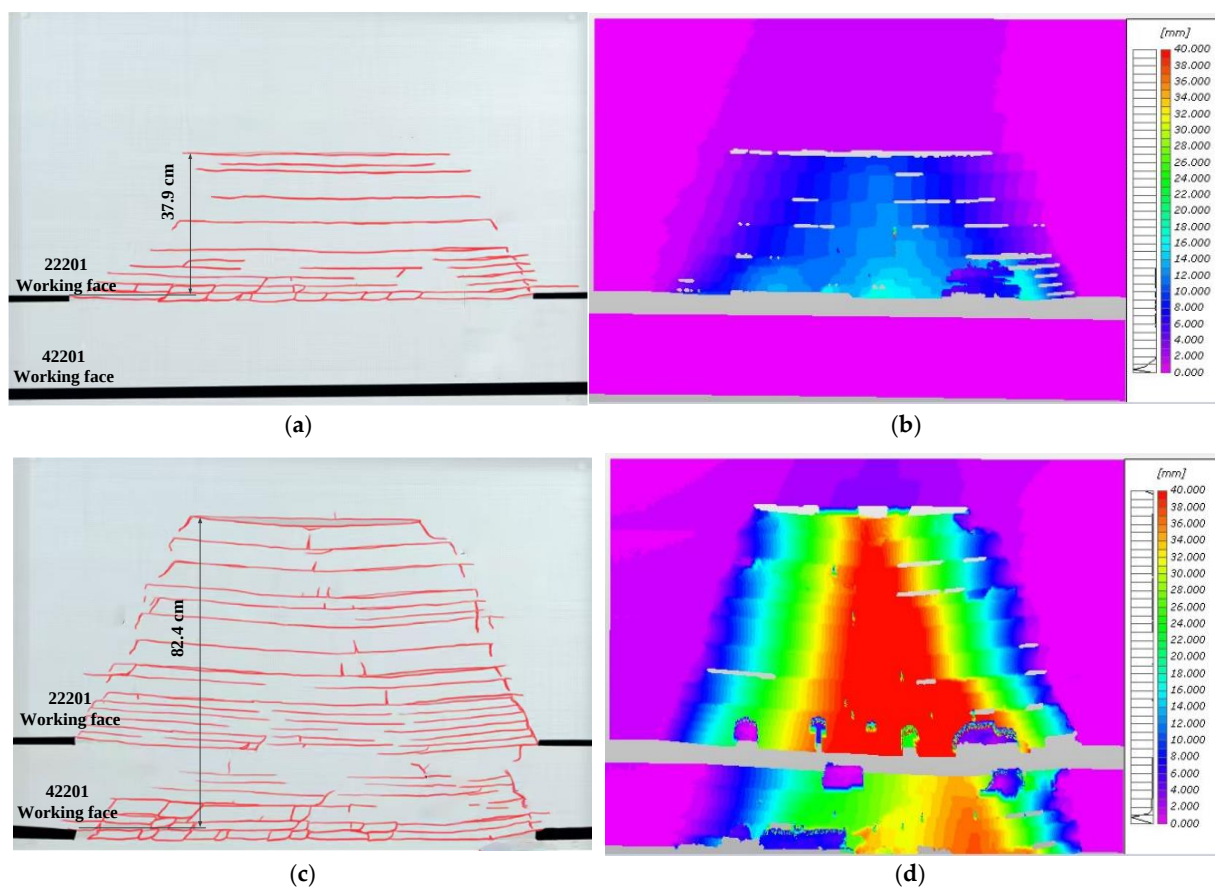


Figure 4. Height of overburden fracture zone after mining in 22201 and 42201 working faces. (a) Overburden rock fracture after No. 22 coal mining; (b) Overburden rock displacement after No. 22 coal mining; (c) Overburden rock fracture after No. 42 coal mining; (d) Overburden rock displacement after No. 42 coal mining.

The overlying rock movement patterns and displacement speckle cloud diagrams after the advancement of the 22201 working face are shown in Figure 4a,b. At this time, vertical and horizontal fissures occurred in nine layers of overlying rock, with a total height of 75.8 m (37.9 cm). According to the speckle image (Figure 4b), it can be seen that the main displacement area of the overburden rock after the mining of the 22201 working face is near the coal pillar and the middle of the goaf area, with the maximum displacement of 3.2 m (16 mm, similar model).

The movement patterns of the overlying rock and the speckle cloud images after the advancement of the 42201 working face are shown in Figure 4c,d. Based on the failure of overlying strata in the 22201 working face (Figure 4a), the mining at the 42201 working face resulted in the formation of new fracture lines at the boundary of the working face and extended upward, and the height of the water-conducting fracture zone of the overlying strata is increased to 164.8 m (82.4 cm, height above No. 42 coal). It can be seen from the speckle image that the subsidence of the rock layer between No. 22 coal and No. 42 coal is about 6.8 m (3.4 cm), and the maximum subsidence of the rock layer overlying No. 22 coal is about 8 m (4 cm).

(2) Model 2

The height of the fracture zone and the displacement of the overlying rock after mining in the 22205, 22206 and 42205 working faces are shown in Figure 5.

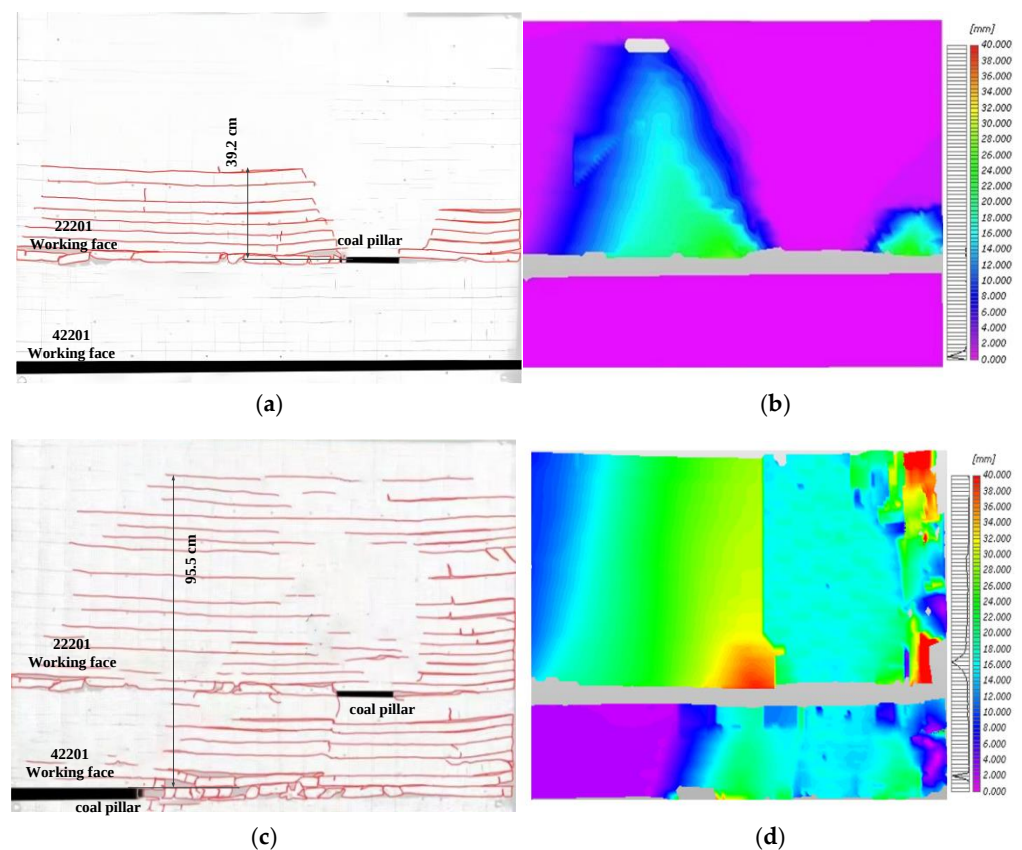


Figure 5. Height of overburden fracture zone after mining in 22205, 22206 and 42205 working faces. (a) Overburden rock fracture after No. 22 coal mining; (b) Overburden rock displacement after No. 22 coal mining; (c) Overburden rock fracture after No. 42 coal mining; (d) Overburden rock displacement after No. 42 coal mining.

The law of overlying strata movement and speckle cloud map after the advancement of the 22205 and 22206 working faces are shown in Figure 5a,b. At this time, there are nine layers of rock in the overlying strata with longitudinal and transverse cracks, and the

height is 78.4 m (39.2 cm). According to the speckle image, the maximum settlement of the overlying strata after the mining of the 22206 working face is 4 m (2 cm), which appears near the coal pillar and the middle of the goaf.

The overlying rock movement patterns and speckle cloud diagrams after the advancement of the 42205 working face are shown in Figure 5c,d. At this time, the main roof collapsed and formed broken rock blocks, and a shear failure zone was formed at the coal pillar of No. 22 coal due to concentrated stress. When No. 42 coal is mined, the height of the fissure zone reaches 164.8 m (82.4 cm). The speckle results show that the location with the largest overlying rock settlement is located at the overlap of the goaf area of the 44205 working face and the 22206 working face, and at the location of the 22206 working face close to the coal pillar, and its value is 8 m (4 mm).

3. Numerical Simulations

Compared with similar simulation experiments, numerical simulation can obtain the height of water-conducting fracture zones under more working conditions at low cost, especially the water inflow rules of underground reservoirs.

3.1. Plastic Damage-Seepage Coupling Model

A reasonable theoretical model is the basis for further implementation of numerical simulations. Rocks have different mechanical responses under different stress states: when the rock is in the elastic deformation stage, stress increases linearly with strain, and the permeability coefficient changes slightly. Once the peak stress is reached, the mechanical properties and permeability coefficient of the rock will change dramatically. To this end, it is necessary to establish a plastic damage constitutive equation.

In order to reflect the deformation and failure behavior of rock under the condition of water pressure and stress at the same time, the effective stress principle is introduced into the elastoplastic damage mechanics, and the following equation is established.

$$\nabla \cdot \sigma^{\text{total}} = \sigma^e + \alpha p I \quad (1)$$

I is the identity matrix. α is the effective stress coefficient, and its expression is

$$\alpha = \begin{cases} 1 - K_{\text{db}}/K_s, & \text{if } d^{(+)} = 0 \\ 1, & \text{if } d^{(+)} > 0 \end{cases} \quad (2)$$

where K_{db} is the drained bulk modulus of the porous medium, K_s is the effective bulk modulus of the solid. σ^e is the effective stress, and its expression is

$$\sigma^e = (I - d)E(\varepsilon - \varepsilon^p) \quad (3)$$

where E is the elastic stiffness matrix and ε^p is the plastic strain vector. d is damage variable and a fourth-order tensor:

$$d = d^{(+)}N^{(+)} + d^{(-)}(I - N^{(+)}) \quad (4)$$

where, $N^{(+)} = \sum_{i=1}^3 h_{\text{ea}}(\sigma_i) n_i \otimes n_i \otimes n_i \otimes n_i$, n_i is the direction vector, and the Heaviside function can be expressed as

$$h_{\text{ea}}(\sigma) = \begin{cases} 1, & \sigma > 0(\text{tension}) \\ 0, & \sigma \leq 0(\text{compression}) \end{cases} \quad (5)$$

It should be emphasized that $d^{(+)}$ and $d^{(-)}$ are tension and compression damage variables, respectively. The damage variables are so distinguished because of two reasons: (1) Tension and compression are the two basic modes of rock failure; (2) Tension-mode fractures are the main controlling factor leading to the mutation of rock seepage.

Based on Equation (5), the total stress can be decomposed into tensile stress $\sigma^{e(+)}$ and compressive stress $\sigma^{e(-)}$. Furthermore, in the effective stress space, Equation (3) can be simplified to:

$$\sigma^{e(+)} = (1 - d^{(+)})E_0\varepsilon_t \quad (6)$$

where, E_0 is the elastic modulus. ε_t and $\sigma^{e(+)}$ can be obtained from the Brazilian split experiment, and

$$\varepsilon_c^p = \varepsilon_c^{\text{in}} - d^{(-)}\sigma^{e(-)} / [(1 - d^{(-)})E_0] \quad (7)$$

where $\varepsilon_c^{\text{in}} = \varepsilon_c - \sigma^{e(-)} / E_0$. $\varepsilon_c^{\text{in}}$, ε_c^p , $d^{(-)}$ are the inelastic strain, plastic strain, and damage variables caused by compressive stress.

The plastic strain ε_c^p in Equation (7) is obtained through the plastic mechanics theory [36].

As mentioned above, tensile damage will profoundly affect the permeability of the rock. When the rock is not damaged, its permeability coefficient k is related to porosity and elastic volume strain ε_{ve} . Once the rock enters the plastic damage stage, fluid mainly migrates through open cracks (i.e., $d^{(+)}$) and is also affected by the plastic volume strain ε_{vp} . The expression is

$$k = \begin{cases} k_{nd} \left\{ (1 + \varepsilon_{ve})^3 / n_p - (1 - n_p) / [n_p(1 + \varepsilon_{ve})^{1/3}] \right\}, & d^{(+)} = 0 \\ (1 - d^{(+)})k_{nd} + d^{(+)}k_d (1 + d^{(+)}\varepsilon_{vp})^3, & d^{(+)} > 0 \end{cases} \quad (8)$$

where k_{nd} and k_d are the permeability coefficient of the undamaged and damaged part of the rock and n_p is porosity.

Through the above Equations (1)–(8), the plastic damage-seepage theoretical model of the mined rock is formed, which lays the foundation for further numerical simulation of the water-conducting fracture zone height and seepage of the mined overlying rock.

3.2. Numerical Models and Results

As mentioned above, the working faces of 22 coal and 42 coal in the Buertai mine have an offset layout. The position of the coal pillar will lead to changes in overlying rock failure forms and seepage volume during mining. Therefore, this article designed three numerical models with coal pillar spacing of 22 coal and 42 coal as $L_{s1} = 0$ m, 60 m, 138 m, respectively. Establishing numerical models in Abaqus 2020 software, the length $\times$ width $\times$ height of each model was 700 m $\times$ 420 m $\times$ 450 m. The upper surface of the model was the free surface, and the other surfaces constrain its normal displacement. Gravity load was applied to the entire model. According to the actual measurement results, the water pressures of the Zhidan Group, Zhiluo Group and Yanan Group aquifers were set to 0.3 MPa, 0.5 MPa and 0.9 MPa, respectively. The rock distribution is shown in Figure 2b. Their mechanical parameters are shown in Table 2.

Table 2. Material parameters.

	Elastic Modulus E_0/GPa	Cohesion c/MPa	Angle of Internal Friction $\varphi/^\circ$	Initial Permeability Coefficient $k_{nd}/(\text{m/s})$	Permeability Coefficient After Damage $k_d/(\text{m/s})$	Initial Porosity $n_p/\%$
Coal	1.63	2.7	27	1.3×10^{-11}	5.6×10^{-9}	3.1
Mudstone	3.58	4.3	32	1.1×10^{-11}	3.2×10^{-9}	2.6
Sandy mudstone	7.22	6.5	38	4.2×10^{-10}	2.9×10^{-7}	4.6
Medium sandstone	14.35	10.3	42	7.6×10^{-9}	1.2×10^{-6}	12.7
Fine sandstone	12.33	11.1	40	2.8×10^{-9}	3.3×10^{-6}	10.3
Siltstone	17.54	8.4	37	8.1×10^{-10}	1.1×10^{-6}	8.3

The numerical simulation results on the transverse section (i.e., I-I section, Figure 2) and longitudinal section (i.e., the advancing direction of the working surface) are shown in Figures 6–8, and their legends are consistent.

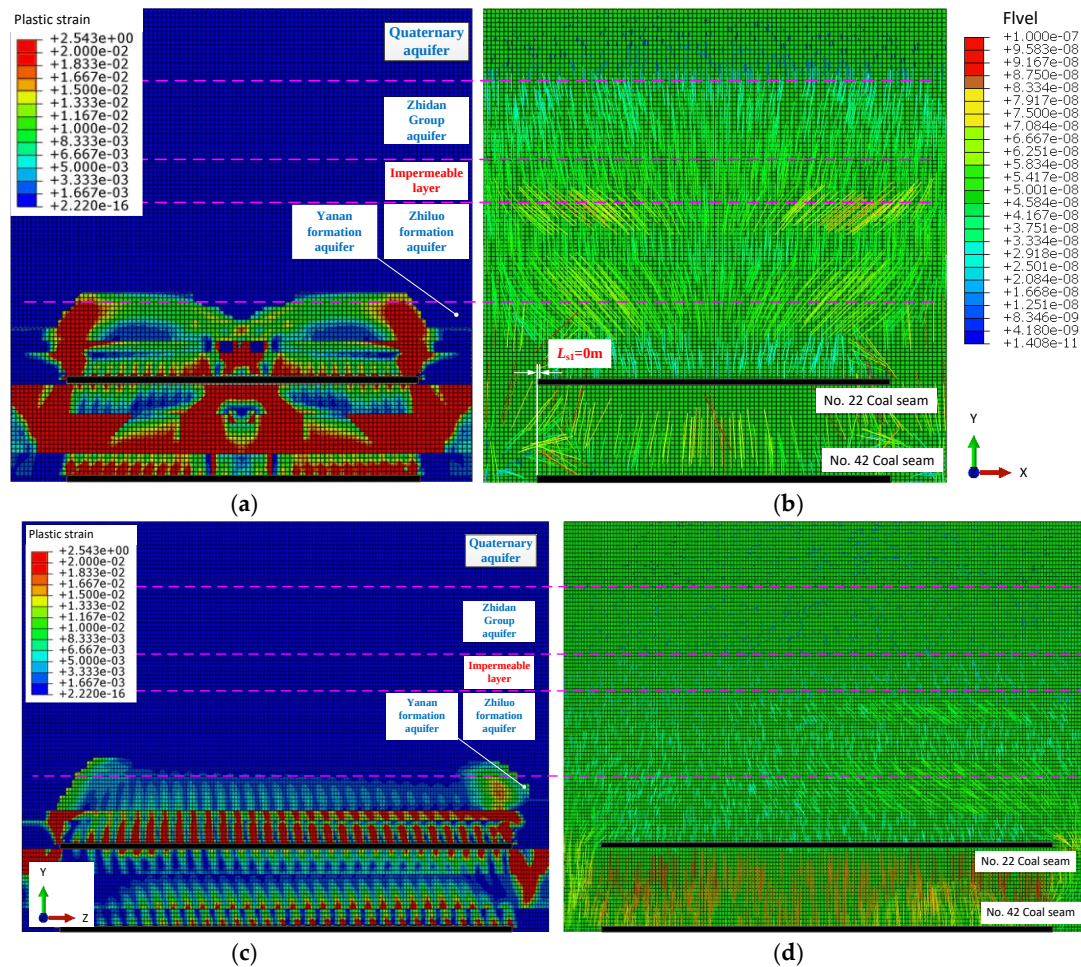


Figure 6. Fluid–solid coupling mechanical response of overlying strata after No. 42 coal mining (coal pillar spacing $L_{s1} = 0$ m). (a) Distribution of plastic zone on transverse section; (b) Seepage velocity on transverse section (unit: m/s); (c) Distribution of plastic zone on longitudinal section; (d) Seepage velocity on longitudinal section.

According to the above diagram, when $L_{s1} = 0$ m, under the mining influence of the 22 coal and the 42 coal, the plastic zone was symmetrically distributed in a saddle shape on the transverse section (Figure 6a,b). The height of the plastic zone in the middle of the working face was low, and the plastic zone near the coal pillar reached the highest value of 158 m. At this time, the groundwater seepage velocity vector was funnel-shaped and symmetrically distributed. The seepage velocity reached the maximum on both sides of the ‘funnel’ in the Zhiluo and Yanan Formations of the 22-coal roof, which was 8.7×10^{-8} m/s, while the seepage velocity in the middle of the funnel was about 5.8×10^{-8} m/s. The average seepage velocity in the sandstone layer of the 42-coal roof was 4.5×10^{-8} m/s. On the longitudinal section (Figure 6c,d), the plastic zone of the overburden rock affected the interior of the Zhiluo Formation at the starting cut and the stop line, and reached the bottom of the Zhiluo Formation at other positions (Figure 6c). The seepage change caused by mining mainly occurred in the Zhiluo Formation and Yanan Formation, and the near-surface aquifer (Zhidan and Quaternary aquifers) was minimally affected by mining. The seepage velocity of each element at the top boundary of the goaf was counted, multiplied by the element area ($4 \text{ m} \times 4 \text{ m}$) and then summed to obtain the water inflow of the 22-coal and 42-coal working faces, which were $133 \text{ m}^3/\text{h}$ and $57 \text{ m}^3/\text{h}$, respectively.

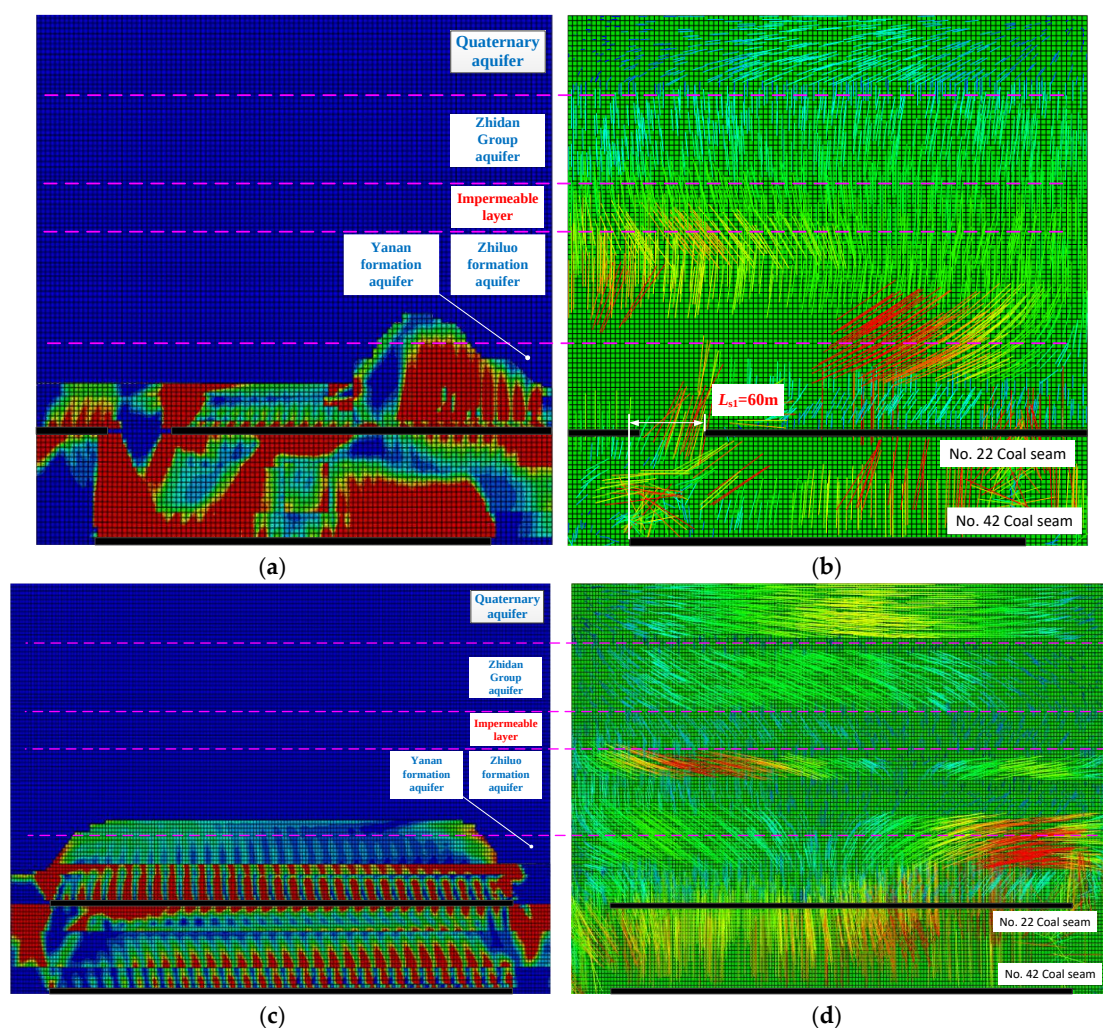


Figure 7. Fluid–solid coupling mechanical response of overlying strata after No. 42 coal mining (coal pillar spacing $L_{s1} = 60$ m). (a) Distribution of plastic zone on transverse section; (b) Seepage velocity on transverse section; (c) Distribution of plastic zone on longitudinal section; (d) Seepage velocity on longitudinal section.

As shown in Figure 7a,b, when $L_{s1} = 60$ m, under the mining influence of the 22 coal and 42 coal, an asymmetric plastic zone distribution form was formed, and the highest point of the plastic zone was located near the 42-coal pillar, which was 174 m. The distribution form of the plastic zone will affect the groundwater seepage to a great extent, resulting in the maximum seepage velocity of 1.2×10^{-7} m/s near the right coal pillar of the 42 coal and in the Zhiluo Formation, while the seepage velocity at other positions of the Zhiluo and Yanan Formations was generally 3.7×10^{-8} m/s. The average seepage velocity in the sandstone layer of the 42-coal roof was small, only 4.2×10^{-8} m/s. On the longitudinal section (Figure 7c,d), the plastic zone of the overburden entered the interior of the Zhiluo Formation (the height of the plastic zone at the section was 166 m). The seepage changes caused by mining mainly occurred in the Zhiluo and Yanan Formations. The groundwater in the near-surface aquifer (Zhidan and Quaternary aquifer) was blocked by the aquiclude and rarely infiltrated into the underground reservoir. The water inflow of the 22-coal and 42-coal working faces were $163 \text{ m}^3/\text{h}$ and $44 \text{ m}^3/\text{h}$, respectively.

As shown in Figure 8a,b, when $L_{s1} = 138$ m, under the mining influence of the 22 coal and 42 coal, an asymmetric plastic zone distribution form was formed. The highest point of the plastic zone was located near the 42-coal pillar, which was 170 m. At this time, the seepage velocity near the coal pillar on the right side of 42 coal and in the Zhiluo Formation

reached the maximum, which was 1.1×10^{-7} m/s, while the seepage velocity at other positions of the Zhiluo and Yanan Formations was generally 2.6×10^{-8} m/s. The average seepage velocity in the sandstone layer of the 42-coal roof increased to 6.5×10^{-8} m/s. On the longitudinal section (Figure 8c,d), the plastic zone of the overburden had entered the interior of the Zhiluo Formation (the height of the plastic zone at the section was 162 m). The groundwater in the near-surface aquifer (Zhidan and Quaternary aquifers) mainly flowed in the stratum, and rarely infiltrated into the underground reservoir. The water inflow of the 22-coal and 42-coal working faces were $116 \text{ m}^3/\text{h}$ and $65 \text{ m}^3/\text{h}$, respectively.

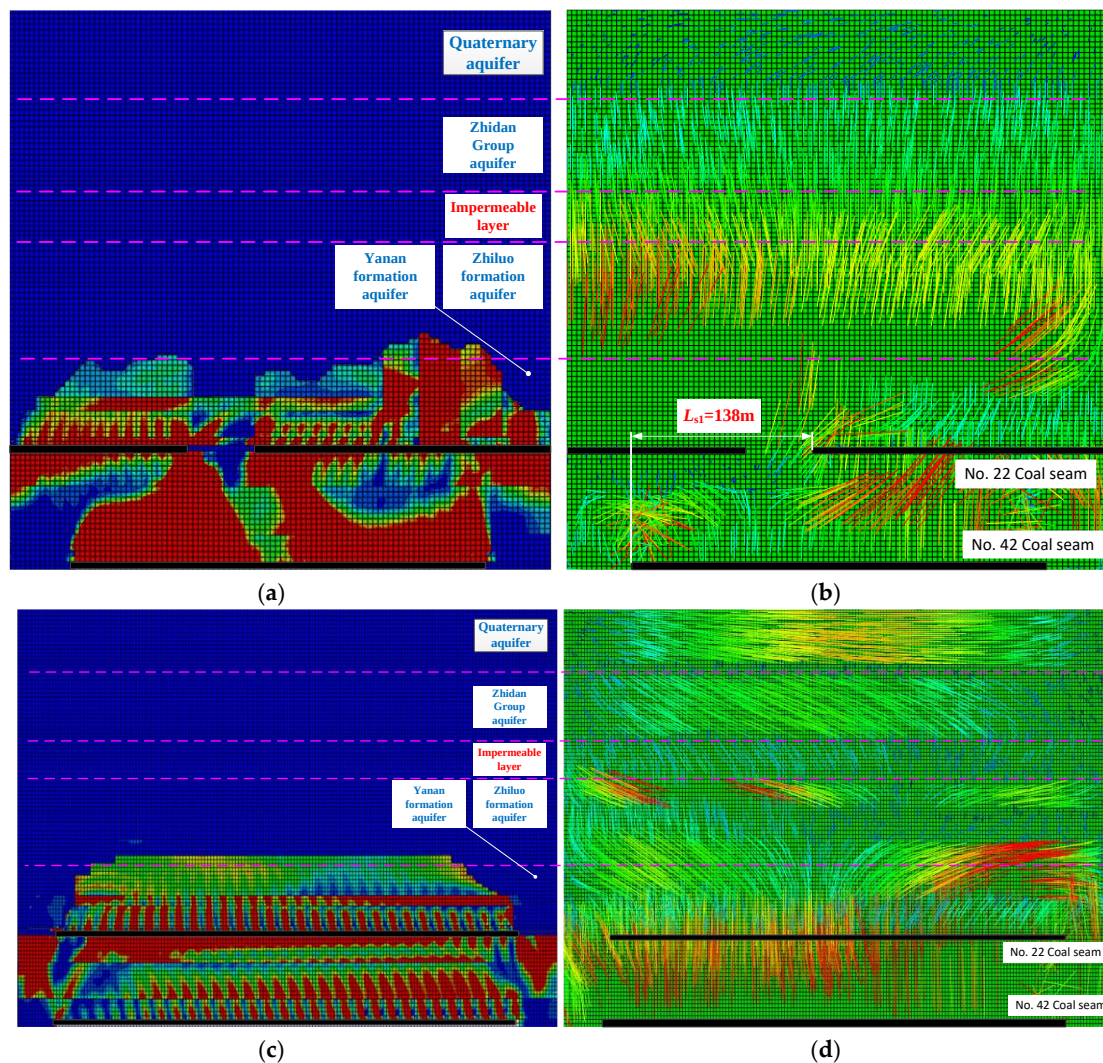


Figure 8. Fluid–solid coupling mechanical response of overlying strata after No. 42 coal mining (coal pillar spacing $L_{s1} = 138$ m). (a) Distribution of plastic zone on transverse section; (b) Seepage velocity on transverse section; (c) Distribution of plastic zone on longitudinal section (d) Seepage velocity on longitudinal section.

4. In-Situ Tests

The accuracy of the above simulation results needs to be verified by in-situ tests. Specifically, it includes two aspects: the height of the water-conducting fracture zone and the water inflow of the underground reservoir.

4.1. Height of Water-Conducting Fracture Zone

The drilling flushing fluid consumption method is used to determine the height of the water-conducting fissures. During coal seam mining, cracks develop in the overlying rock,

which greatly increases its permeability. If geological drilling is performed in fractured rock, the height of the water-conducting fractures can be determined by monitoring changes in the loss of flushing fluid (a fluid used to reduce drill bit temperature and protect the borehole).

On this basis, the following criteria are further established to determine the fracture's height:

- (1) At a certain position, the consumption of flushing fluid in the borehole increases rapidly, or there is no flushing fluid in the hole. Alternatively, after the borehole is blocked, there is still a phenomenon of all flushing fluid leakage when drilling again.
- (2) With the increase of drilling depth, the water level in the borehole decreases faster.

According to the numerical simulation results, combined with the mining situation of the working face (Figures 6–8), three boreholes (marked TC2, TC3 and TC4) were arranged on the 22206, 22205 and 42205 working faces (Figure 9). At this time, the distance between the coal pillars of 22 coal and 42 coal is 138 m. Among them, the TC2 hole was used to test the fracture's height when No. 22 coal was mined (only the 22206 working face was mined during the in-situ tests in June 2024, and the 42206 working face has not yet been mined), and the TC3 and TC4 holes were used to test the height of the water-conducting fracture zone when the 22205, 22206 and 42205 working faces were mined.

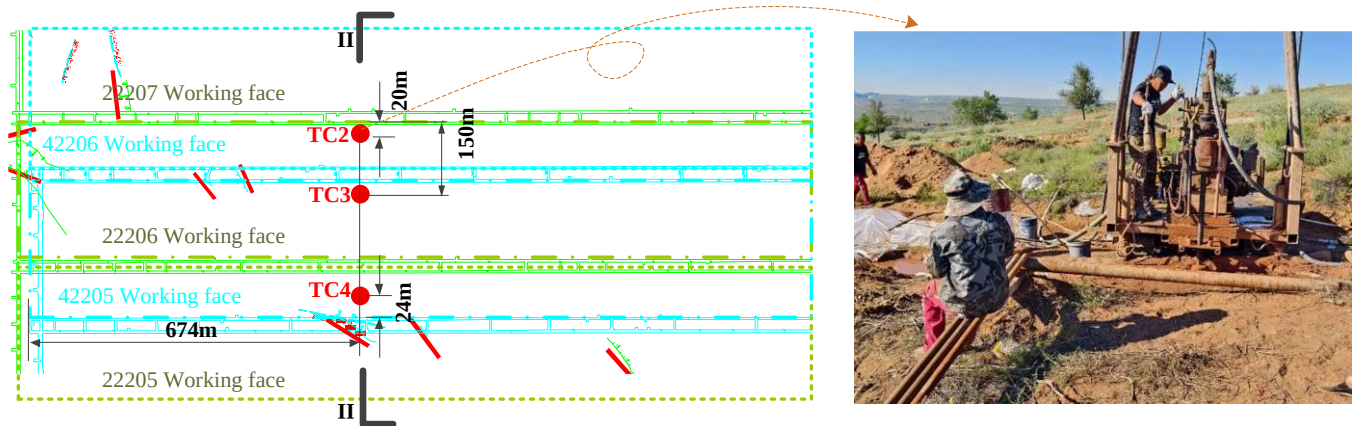


Figure 9. Locations of the three drill holes in the in-situ tests.

During the drilling process, the consumption of flushing fluid was observed every 5 m of drilling. The results are shown in Figure 10.

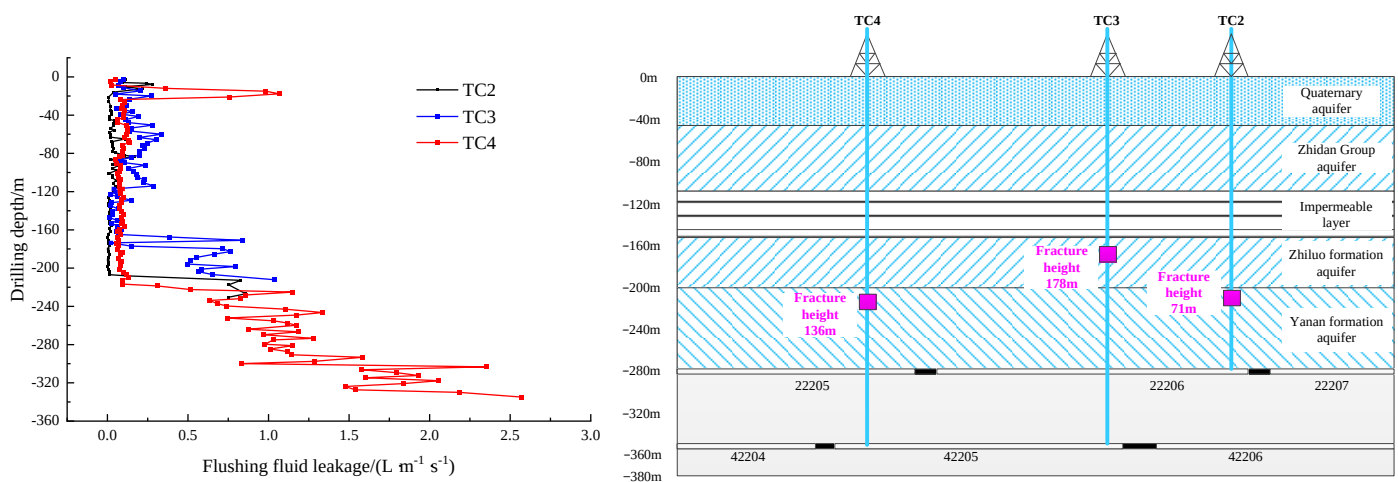


Figure 10. Leakage of flushing fluid during drilling process.

- (1) During the TC2 drilling process, the leakage of flushing fluid was about 0.1~0.3 L/(m·s) when the hole depth was 0~12.5 m. This is because the Quaternary soil layer has large porosity and strong permeability. When the hole depth was 12.5~120 m, the leakage of flushing fluid was 0.02~0.15 L/(m·s), indicating that the Zhidan Group sandstone aquifer was less affected by mining. When the hole depth was 120~233 m, the leakage of flushing fluid decreased to 0~0.02 L/(m·s), indicating that the opening of rock fractures at a depth of 12.5 m~233 m was small during mining. Once the hole depth increased to 233~282 m, the leakage of flushing fluid suddenly increased from 0.007 L/(m·s) to more than 0.6 L/(m·s), which was 30 times the liquid consumption of shallow rock formations. It can be seen that below the hole depth of 233 m was the area where fractures in the hole wall were relatively developed. The leakage rate of the strata affected by uncollected mining generally does not exceed 0.3 L/(m·s), therefore, the height of the water-conducting fracture zone in the 22206 working face is 71 m. At this time, the aquifers of the Zhiluo Formation and Zhidan Group remain intact.
- (2) During the TC3 drilling process, the leakage of flushing fluid at the hole depth of 0~121 m was about 0.1~0.36 L/(m·s), indicating that No. 42 coal mining can cause a certain degree of damage to the Zhidan Group sandstone layer. When the hole depth was 121~165 m, the leakage of flushing fluid was 0.02~0.1 L/(m·s), indicating that the impermeable layer (Figure 9) was relatively intact. Once the hole depth increased to 165~171 m, the flushing fluid leakage suddenly increased from 0.07 L/(m·s) to 0.84 L/(m·s), and as the hole depth increased, the leakage of flushing fluid was maintained in the range of 0.5~0.8 L/(m·s). In summary, the water-conducting fractures were developed below the drilling depth of 171 m. Therefore, under the combined influence of repeated mining and No. 42 coal pillars, the height of the water-conducting fracture zone in the 42,205 working face is 178 m.
- (3) During the TC4 drilling process, the leakage of flushing fluid increased rapidly from 0.03 L/(m·s) to 1.06 L/(m·s) at the hole depth of 0~18 m. The reason is that the Quaternary soil layer has large porosity. At a depth of 18 m~216 m, the flushing fluid leakage remained at 0.08 L/(m·s), indicating that the Zhidan aquifer and the impermeable layer were not destroyed. When the hole depth was 216~228 m, the flushing fluid leakage increased from 0.09 L/(m·s) to 0.85 L/(m·s). When the hole depth was 228~291 m, the flushing fluid leakage was 0.7~1.4 L/(m·s). When the hole depth was 291~297 m, the flushing fluid leakage increased to more than 2.1 L/(m·s). In short, the fractures were more developed in the depth of 216 m. Therefore, under the repeated mining disturbance of the 22205 and 42205 working faces, and under the combined influence of coal pillars of No. 42 and 22 coal, the height of the water-conducting fracture zone of the 42205 working face was 136 m.

In a word, the in-situ experimental results show that the height of the water-conducting fracture zone of the overlying strata under the condition of mining the 22206 working face is 71 m, the fracture's height under the condition of combined mining of the 22206 and 42205 working faces is between 136 m and 178 m, and the fracture's height under the influence of No. 42 coal pillars is larger (TC3 borehole, Figure 9). The numerical simulation is close to the above in-situ results, indicating the rationality of the numerical results. In addition, according to the above results, the maximum height of the water-conducting fractures under repeated mining of multiple coal seams is 178 m, which means that the impermeable layer (Figure 9) about 200 m vertically away from the No. 42 coal seam has not been destroyed, and the near-surface aquifer (Zhidan Formation) above it has not been destroyed. Therefore, the multi-seam mining in Buertai Coal Mine has little effect on the surface ecological environment.

4.2. In-Situ Test of Water Inflow

In this section, the in-situ observation of groundwater reservoir water inflow includes two aspects: (1) the water inflow of the whole mine, (2) The water inflow of a single working

face. For the former, if the total water inflow of the mine is too small, or even cannot meet the water use of the mine itself, it shows that the construction of underground reservoirs is of little significance. For the latter, it can be used to test the rationality of numerical simulation results.

(1) The water inflow of the whole mine

At present, the average industrial water consumption of the Buertai mine is $140 \text{ m}^3/\text{h}$, and the average domestic water consumption of employees is $1.90 \text{ m}^3/\text{h}$. Of the above $141.9 \text{ m}^3/\text{h}$ water volume, about $45 \text{ m}^3/\text{h}$ is purified and then injected into the goaf (Figure 1). Therefore, the actual withdrawal volume from the underground reservoir is $96.9 \text{ m}^3/\text{h}$. When the amount of water flowing into the goaf exceeds $96.9 \text{ m}^3/\text{h}$, the underground reservoir can be used for a long time.

In order to verify the above results, we carried out in-situ observations of underground reservoir water volume from January 2020 to June 2023. Considering that all the groundwater in the goaf of No. 22 coal and No. 42 coal must pass through the central water storage, its function is to collect the groundwater of the whole mining area; once the water volume exceeds the warning value, the water in the water storage will be discharged to the surface through pumps. Therefore, the observation position is arranged here, and the average flow rate of any time period can be obtained through the flow meter. The total water consumption of the mine is the sum of the flow of the No. 22 coal and No. 42 coal, and the results are shown in Figure 11. It shows that the water inflow of underground reservoir has remained above $500 \text{ m}^3/\text{h}$ in the past 3.5 years, which meets the needs of mine production.

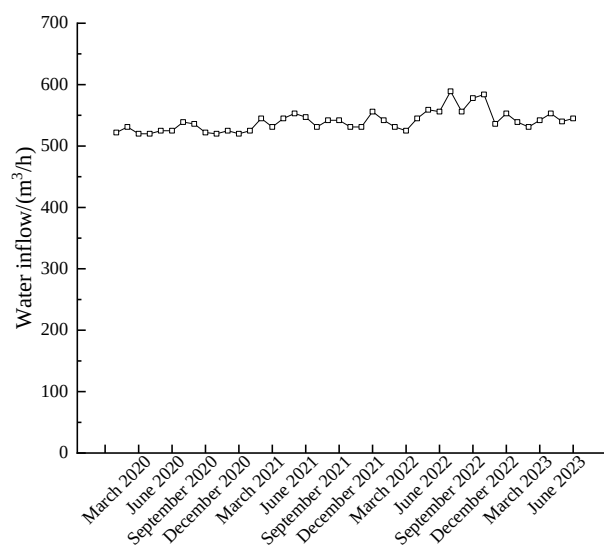


Figure 11. Water inflow of Buertai Coal Mine.

In addition, the agricultural or surface vegetation irrigation water consumption near the Buertai mine is about $4.11 \text{ m}^3/(\text{h} \cdot \text{ha})$ per hectare (calculated as $4500 \text{ m}^3/\text{ha}$ per irrigation, 8 times a year). Therefore, the underground reservoir in the goaf of the Buertai mine can be used to irrigate about 98 hectares of farmland or surface vegetation in addition to the coal mine itself (that is, the domestic water of employees, the water for coal mine production). In this way, economic and social benefits can be achieved.

(2) The water inflow of a working face

Based on the in-situ observation data, the amount of water flowing into the working face during mining was obtained, as shown in Figure 12.

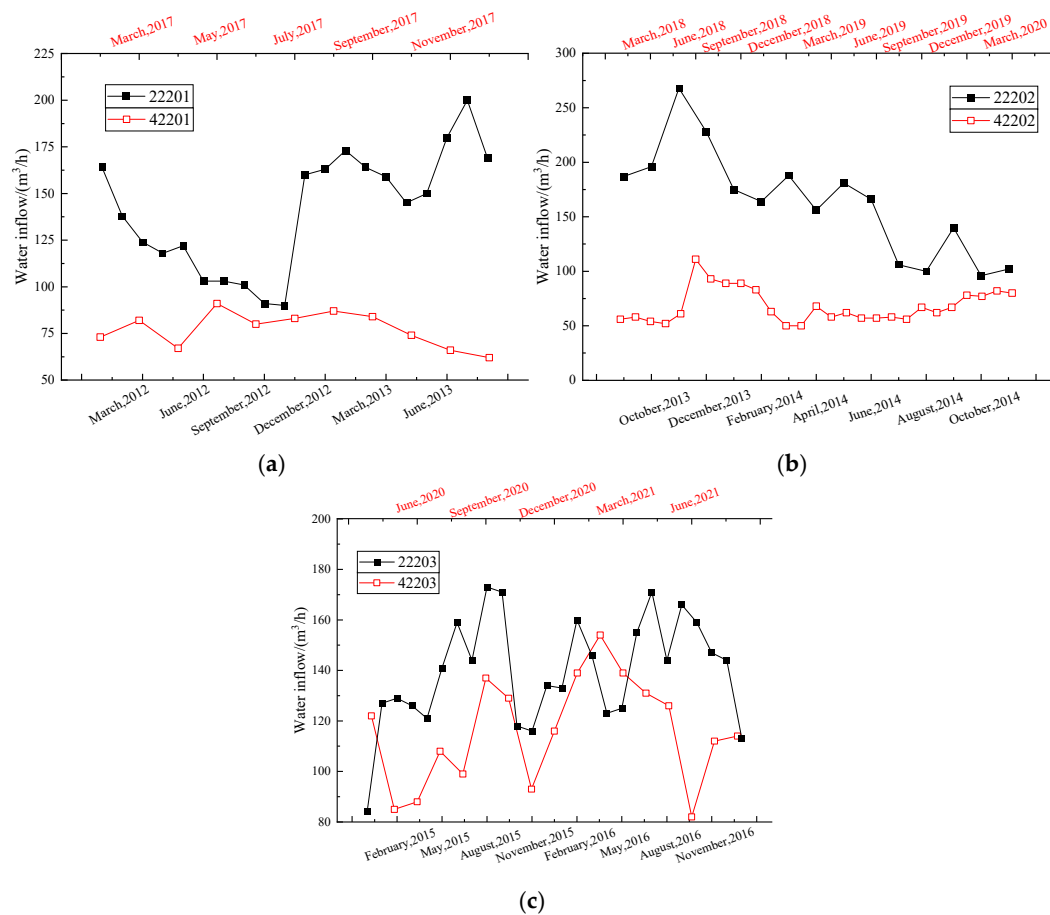


Figure 12. Water inflow during working face mining. (a) The water inflow of the 22201 and 42201 working faces; (b) The water inflow of the 22202 and 42202 working faces; (c) The water inflow of the 22203 and 42203 working faces.

The average water inflow values during mining in the 22201 and 42201 working faces were approximately $145 \text{ m}^3/\text{h}$ and $74 \text{ m}^3/\text{h}$, respectively. The average water inflow values during mining in the 22202 and 42202 working faces were approximately $176 \text{ m}^3/\text{h}$ and $77 \text{ m}^3/\text{h}$, respectively. The average water inflow values during mining in the 22203 and 42203 working faces were approximately $138 \text{ m}^3/\text{h}$ and $112 \text{ m}^3/\text{h}$, respectively.

5. Conclusions

- (1) Under the repeated mining of the 22 coal and 42 coal in the Buertai mine, the maximum height of the water-conducting fracture zone is 178 m, which has little effect on the near-surface aquifer.
- (2) The water inflow volumes of the 22- and 42-coal working faces obtained by numerical simulation was $116\sim 163 \text{ m}^3/\text{h}$ and $44\sim 65 \text{ m}^3/\text{h}$, respectively. The maximum value of the numerical simulation and the in-situ results deviated by 7.4% and 41.9%, respectively.
- (3) During the 22-coal mining period, the groundwater in the Zhidan and Zhiluo Formations is mainly vertical discharge. During the 42-coal mining period, the groundwater in the Yanan Formation mainly flows horizontally and is discharged in the plastic zone of the overburden rock, which causes the difference in the simulation and in-situ results.
- (4) The water inflow of the Buertai mine is about $500 \text{ m}^3/\text{h}$. If an underground reservoir in the coal goaf is built here, it will not only be able to meet the mine production and miners' domestic water needs, but also irrigate the nearby 98 hectares of farmland, which provides a useful solution for the realization of coal mining-water storage-surface ecological sustainable development in semi-arid areas.

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