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Research Article

Study on Deformation and Fracture Evolution of Underground Reservoir Coal Pillar Dam under Different Mining Conditions

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Coal mine underground reservoir water storage technology is an effective technical way to achieve high efficiency of coal mining and protection of water resources. The stability of coal pillar dam plays a decisive role in the safe and stable operation of underground reservoirs. Mining of adjacent working faces and long-term water erosion are the main influencing factors of stability of coal pillar dam. In this paper, a fluid-solid coupling calculation model for the deformation and evolution of coal pillar dam was established by FLAC3D numerical simulation software and the underground brine reservoir of Lingxin Coal Mine of Shenning group as an engineering background. The paper studied systematically the deformation, failure, and stress evolution of the dam with coal pillars soaked in water for a long time under different working face inclining length, coal pillar width, mining height, and water pressure. The simulation results showed that the degree of deformation and failure of the coal pillar dam continued to increase with the continuous advancement of the working face. The plastic zone of the coal pillar dam was increased by approximately 23.53%, the maximum vertical stress was increased by approximately 95.78%, and the maximum vertical deformation was increased by approximately 68.18%. The influence of each factor on the deformation and failure of overburden strata is quite different. The development range of plastic zone, the maximum vertical stress, and the maximum vertical deformation were increasing with the increased of working face inclined length and mining height. The increasing width of coal pillar would lead to the decrease of maximum vertical stress. The increase of water pressure would lead to the decrease of maximum vertical deformation. It can be seen that the inclined length of the working face is the main factor affecting the deformation and failure of the coal pillar dam. Coal pillar width and mining height are the main factors affecting the development of plastic zone. This study reveals the law of deformation and fracture evolution of coal pillar dam under different mining conditions, which can provide a reference for the design of coal pillar dam of coal mine underground reservoir.

1. Introduction

A major problem in green mining of China is the protection and utilization of water resources, especially in western regions such as Inner Mongolia, Shanxi, Shaanxi, Ningxia, and Xinjiang. The proven coal resources in these regions account for about 80% of the country's total reserves. However, due to its location in the arid-semiarid zone of China, water resources have become the dominant factor restricting coal mining and ecological protection in these regions [1–9]. Therefore, in order to reduce the loss of water resources caused by mining, Gu and others propose to store water by using underground goaf, by connecting the safety coal pillars at the borders of the goaf with artificial dams to form underground storage reservoirs. This technology plays a key role in many fields, such as preventing and controlling water disasters, reducing surface losses, and ensuring the stability of roadways. It is an effective way to solve the protection

Columnar lithology		Thickness (m)	Lithology description
	Coarse sandstone	18.0	Light gray, gray-green, the main components are feldspar, quartz
	Siltstone and fine sand interbed	10.0	Grayish green and grayish green with purple spots
	Coarse sandstone	2.0	Light gray, gray-green, the main components are feldspar, quartz
	Siltstone and fine sand interbed	11.0	Grayish green and grayish green with purple spots
	Mudstone	7.0	Gray green, brown red and others
	Siltstone and fine sand interbed	17.5	Gray-green, purple-grey, brown-gray thick layer to massive fine grain, siltstone
	Mudstone	4.5	Gray green, brown red and others
	Coarse sandstone	3.0	Light gray, gray-green, the main components are feldspar, quartz
	Mudstone	4.5	Gray green, brown red and others
	14# coal seam	2.5	The thickness is 2.2~2.9 m, can be mined in the whole mine field
	Siltstone and fine sand interbed	20.0	Gray-green, purple-grey, brown-gray thick layer to massive fine grain, siltstone

Figure 1: Geological histogram.

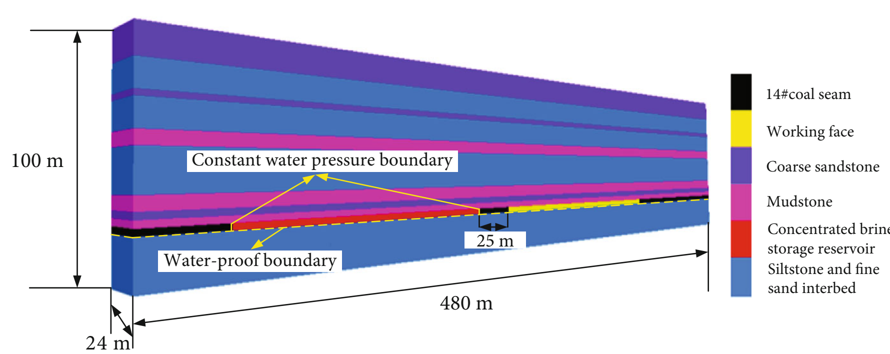


Figure 2: FLAC3D model diagram.

and utilization of water resources in ecologically fragile areas in the west [10–15].

The coal safety pillars at the boundary of the goaf play an important part of the reservoir dams, and its stability directly determines the normal operation of the underground water reservoir. The stability of coal pillar dam is essentially the deformation and failure of the dam under the influence of overburden pressure, water pressure, and coal mining [16–22]. And scholars at home and abroad have achieved many research results about this. Gu et al. [23] explored the destruction form of coal pillar dams through similar simulation tests under dynamic loading conditions and proposed the safety factor of coal pillar dams in underground water reservoirs. Zhang [24] analyzed the safety for the dam of the groundwater reservoir by establishing a mathematical model for dam safety analysis. Through numerical simulation research, Yao et al. [25] found that the water content, buried depth, and coal seam mining thickness all have a great influence on the width of the coal pillar dam. Bai et al. [26] found that under the influence of water storage pressure in goaf and the pressure of the overlying strata, the bottom of the outer surface and the top of the inner surface of the artificial dam were prone to instability and damage, and instability in other locations was less likely. Wang et al. [27] found that the development area and depth of the plastic zone of coal pillar surrounding rock increased significantly under the dynamic load, and the vertical stress extreme point developed in the depth direction. Most of the above studies are aimed at the stability of coal pillar dam under the effect of overburden pressure and water pressure, and there is still insufficient research on the influence of mining on adjacent working faces. If the law of deformation and fracture evolution of coal pillar dam under different mining conditions can be grasped and by combining with the research results of the influence of overburden pressure and water pressure, so the correlative design of coal pillar dam can be carried out in order to achieve the best effect.

In this paper, FLAC3D fluid structure coupling calculation model is established based on the engineering background of underground concentrated brine reservoir in Lingxin Coal Mine of Shenning group. The laws of deformation, fracture, and stress evolution of coal pillar dam under different mining conditions are studied. This study provides a reference for the design of coal pillar dam of underground reservoir.

2. Engineering Geological Conditions

Lingxin Coal Mine is located in Ciyaobao Town, Lingwu City, Ningxia Hui Autonomous Region. It is a key construction project of the "Eighth Five-year Plan" of China, with a designed production capacity of 3.2 million tons per year. It is the main production mine of Shenning Company. In order to save water resources and reduce water pollution, Lingxin Coal Mine constructed a high-mineralization mine water quality and utilization treatment station underground in the first mining area. The purpose is to recycle 85% of Lingxin coal mine water and permanently store 15% of concentrated brine in underground goaf. To this end, Lingxin Coal Mine built an underground water reservoir in the north wing of the first mining area to store concentrated brine. The water level of the reservoir is +1050 m to +1145 m, and the head pressure is 0.9842 MPa. Because the location of the brine storage is affected by the mining and water pressure of the adjacent working face all the year round, the requirements for the coal pillar dam are also relatively high.

The main coal seam in the first mining area is 14# coal, which is located at the level of +1050 m underground, and the mining ended in 2008. The average thickness of 14# coal is 2.8 m. The thickness of the coal seam is simple in structure, with a bedded structure and the lower coal quality hardness. The immediate roof is mudstone, and the upper part and the floor are fine sand and rock interbedded. The specific histogram is shown in Figure 1. In the first mining area, the strike length of working face is 1040.8 m, the inclined length is 180~200 m, and the width of protective coal pillar between working faces is 25 m.

3. Numerical Simulation

3.1. Model Building. According to the geological profile of 14# coal in Lingxin Coal Mine, the abovementioned concentrated brine storage reservoir was used as the research prototype, and a three-dimensional numerical model was established by using the finite difference software FLAC3D. The model is shown in Figure 2, and the size is determined to be $\text{length} \times \text{width} \times \text{height} = 480\,\text{m} \times 24\,\text{m} \times 100\,\text{m}$. A total of 351,5000 grids and 3682710 nodes are divided. The physical and mechanical properties of each strata are set according to reference [28].

Table 1: Simulation scheme of orthogonal experiment.

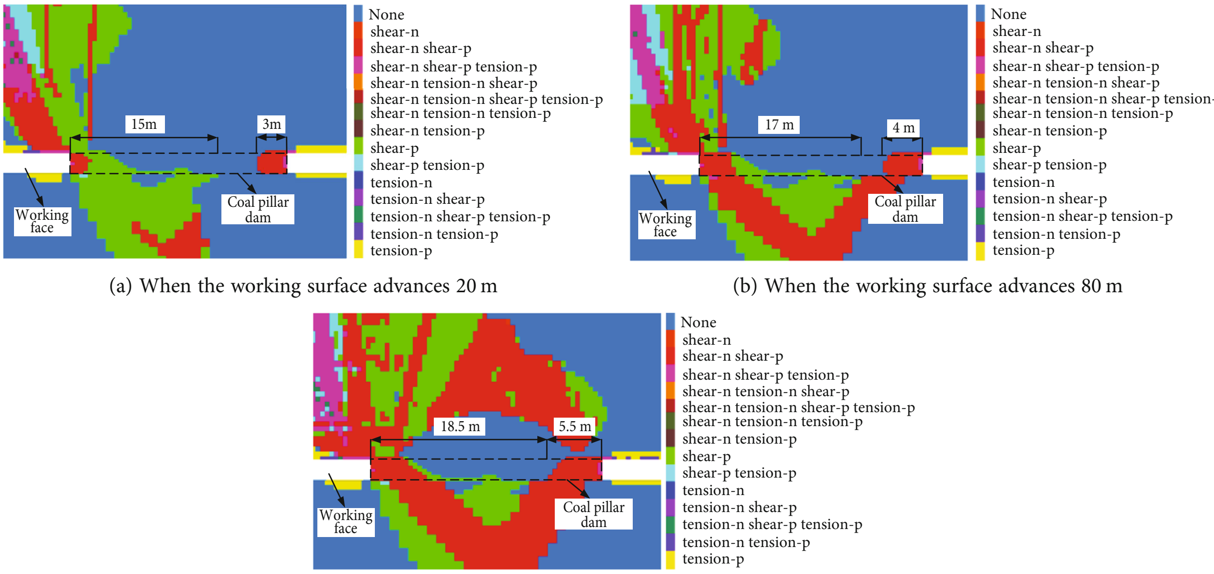
Test	Length of working face/m	Width of coal pillar/m	Mining height/m	Water pressure/MPa
1	100	20	1.5	0.5
2	100	25	2	1
3	100	30	2.5	1.5
4	100	35	3	2
5	150	20	2	1.5
6	150	25	1.5	2
7	150	30	3	0.5
8	150	35	2.5	1
9	200	20	2.5	2
10	200	25	3	1.5
11	200	30	1.5	1
12	200	35	2	0.5
13	250	20	3	1
14	250	25	2.5	0.5
15	250	30	2	2
16	250	35	1.5	1.5

Set an 80 m area on the left and right sides of the model to reduce the boundary effect. Model boundary conditions: (1) mechanical boundary, the X direction of the model constrains the left and right boundary displacements, the Y direction constrains the front and rear boundary displacements, and the Z direction constrains the lower boundary displacements. The fix command is used to control the model boundary velocity, and the upper boundary of the model is imposed with a self-weight stress of 5.35 MPa in the overlying strata. (2) Seepage boundary conditions, the bottom plate of the reservoir is the water-proof boundary, and the two sides are the boundary of constant water pressure, and a certain water pressure is applied here according to the experimental design.

The Mohr-Coulomb yield criterion is used to judge the deformation and fracture evolution of coal pillar dam under different mining conditions.

3.2. Design of Orthogonal Experiment Simulation Scheme. Orthogonal experiment method is a design method to study multifactor and multilevel. It can select some representative level combinations to test and analyze the results to find the optimal level combination.

The stability of the coal pillar dam is often affected by coal mining. Considering that there is a working face on the side of the reservoir and the coal pillar dam is immersed in water for a long time, therefore, the influencing factors of the stability of the coal pillar dam are selected as the inclined length and the mining height of the adjacent working face, the width of the coal pillar dam, and the water pressure exerted on the coal pillar dam. According to the actual geological and production conditions, the above four factors take 4 levels, the permeability coefficient of the coal pillar is 1.36×10^{-6}, the working face is simulated by step mining,



(a) When the working surface advances 20 m

(b) When the working surface advances 80 m

(c) When the working surface advances 180 m

FIGURE 3: Cloud diagram of plastic zone change during mining.

the orthogonal test has a total of 4 factors, and each factor has 4 levels. Regardless of the interaction between factors, the $L16$ (4^4) orthogonal Tab. is selected, and the test indicators are the development height of the plastic zone, maximum vertical stress, and maximum vertical deformation of the coal pillar dam, and the test scheme under different parameter combinations is numerically simulated. The orthogonal experiment simulation scheme is shown in Table 1.

4. Analysis of Simulation Results

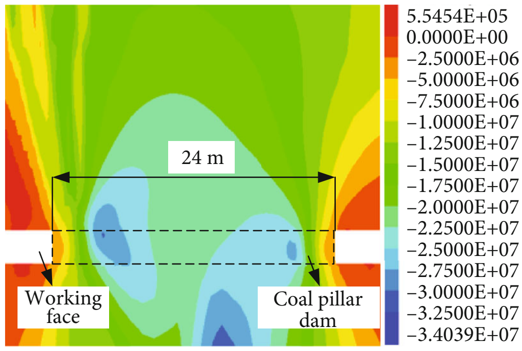
4.1. Evolution of Deformation and Fracture of Coal Pillar Dam during Mining. In the simulation calculation, the step excavation method is adopted to mine the working face. The experiment 14 is used as an example to analyze the law of deformation and fracture evolution of the coal pillar dam. The plastic zone distribution cloud map, vertical stress cloud map, and vertical deformation cloud map of some excavation stages are as shown in Figures 3–5.

It can be seen from Figure 3 that when the face is pushed 20 m, the coal pillar face is slightly damaged, there is a plastic zone of about 3 m, and the top and floor of the face are also partially damaged; when the face is pushed 80 m, the plastic zone on the working face side of the coal pillar dam continues to develop into the interior of the coal pillar dam. The plastic zone in the lower part of the dam is connected with the reservoir side, and the plastic zone appears in the side wall angle of the coal pillars of the working face and continues to extend deeper; the roof damage range is further expanded; when the working face is pushed 180 m away, the plastic zone in the coal pillar dam is further expanded, and the plastic zone above the coal pillar dam is combined with the plastic zone on the side of the working face. During the mining process, with the advancement of the working face, the horizontal development range of the plastic zone on the reservoir side continues to increase. It can also be seen from the figure that the failure mode of the coal pillar dam is mainly shear failure, and the horizontal development range of the plastic zone in the coal pillar dam has expanded by about 23.53%.

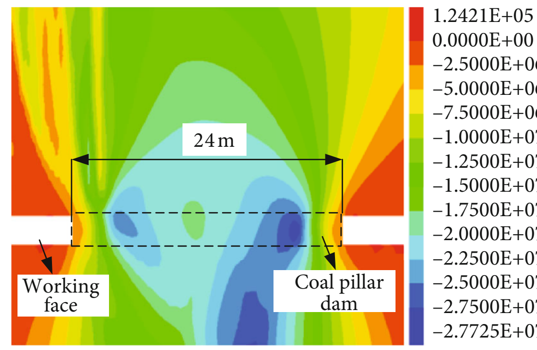
It can be seen from Figure 4 that as the working face continues to push, the maximum vertical stress in the coal pillar dam continues to increase. When the working face is pushed 20 m, the maximum vertical stress in the coal pillar dam is 27.73 MPa, the maximum vertical stress is mainly distributed on the reservoir side, and the side of working face is slightly distributed; when the working face is pushed 80 m, the maximum vertical stress is 34.04 MPa. The maximum vertical stress is mainly distributed on the working face side, but less on the reservoir side. When the working face is pushed 180 m, the maximum vertical stress is 25.14 MPa, and the maximum vertical stress on the side of the working face is further increased. The working face is pushed from 20 m to the end of mining, and the maximum vertical stress is increased by about 95.78%.

It can be seen from Figure 5 that when the working face is pushed 20 m, the maximum vertical deformation of the coal pillar dam is about 0.66 m; when the working face is advanced by 80 m, the maximum vertical deformation of the coal pillar dam is about 0.84 m. When the working face is pushed 180 m, the maximum vertical deformation of coal pillar dam is about 1.03 m. The working face was pushed from 20 m to the end of mining, and the maximum vertical deformation increased by about 68.18%.

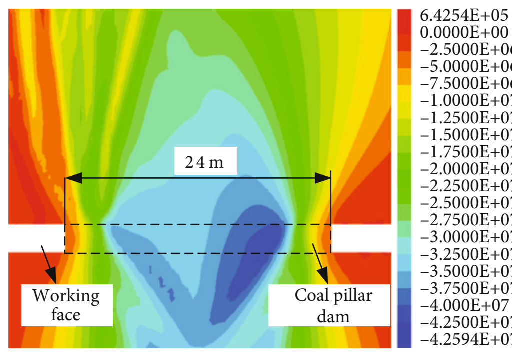
4.2. Influence of Various Factors on Deformation and Fracture of Coal Pillar Dam. The simulation is carried out according to the experimental design, and the development range of the plastic zone, vertical stress, and vertical deformation inside the coal pillar dam under different mining conditions were obtained, respectively. In some of the



(a) When the working surface advances 20 m

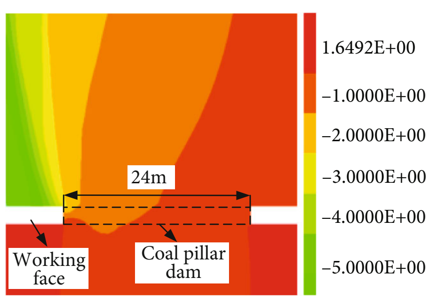


(b) When the working surface advances 80 m

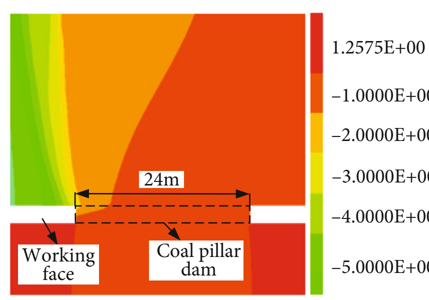


(c) When the working surface advances 180 m

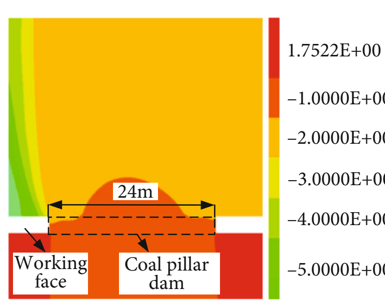
Figure 4: Stress cloud diagram during mining.



(a) When the working surface advances 20 m



(b) When the working surface advances 80 m

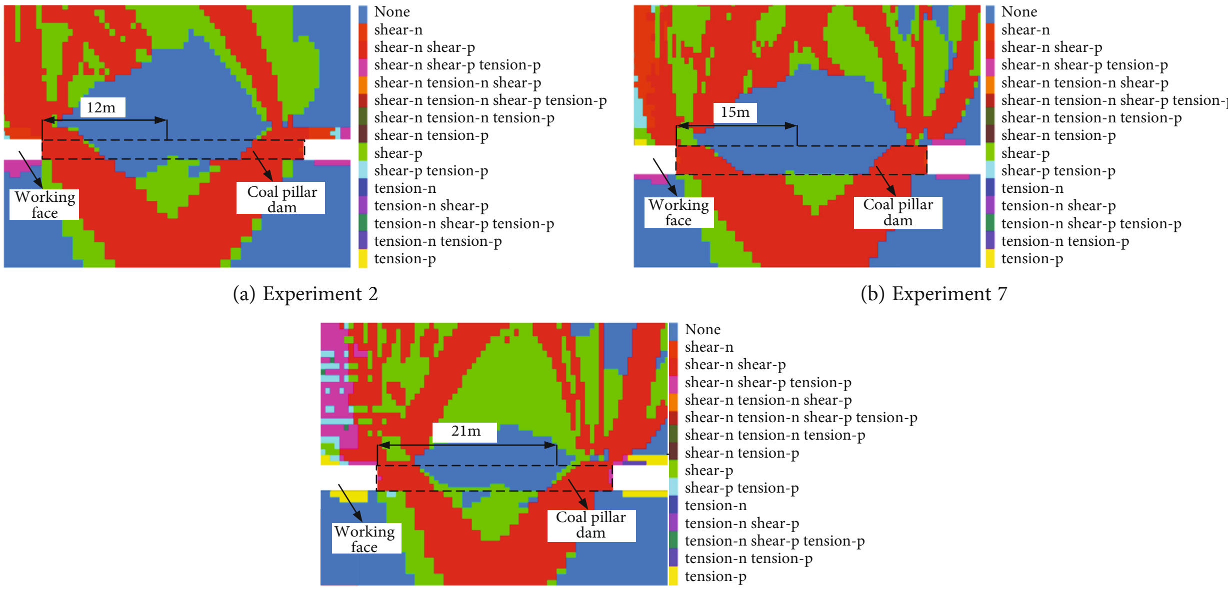


(c) When the working surface advances 180 m

Figure 5: Deformation cloud diagram during mining.

simulation results, the distribution cloud map of the plastic zone, stress distribution cloud map, and deformation distribution cloud map of coal pillar dam are shown in Figures 6–8, respectively. The simulation results are shown in Table 2.

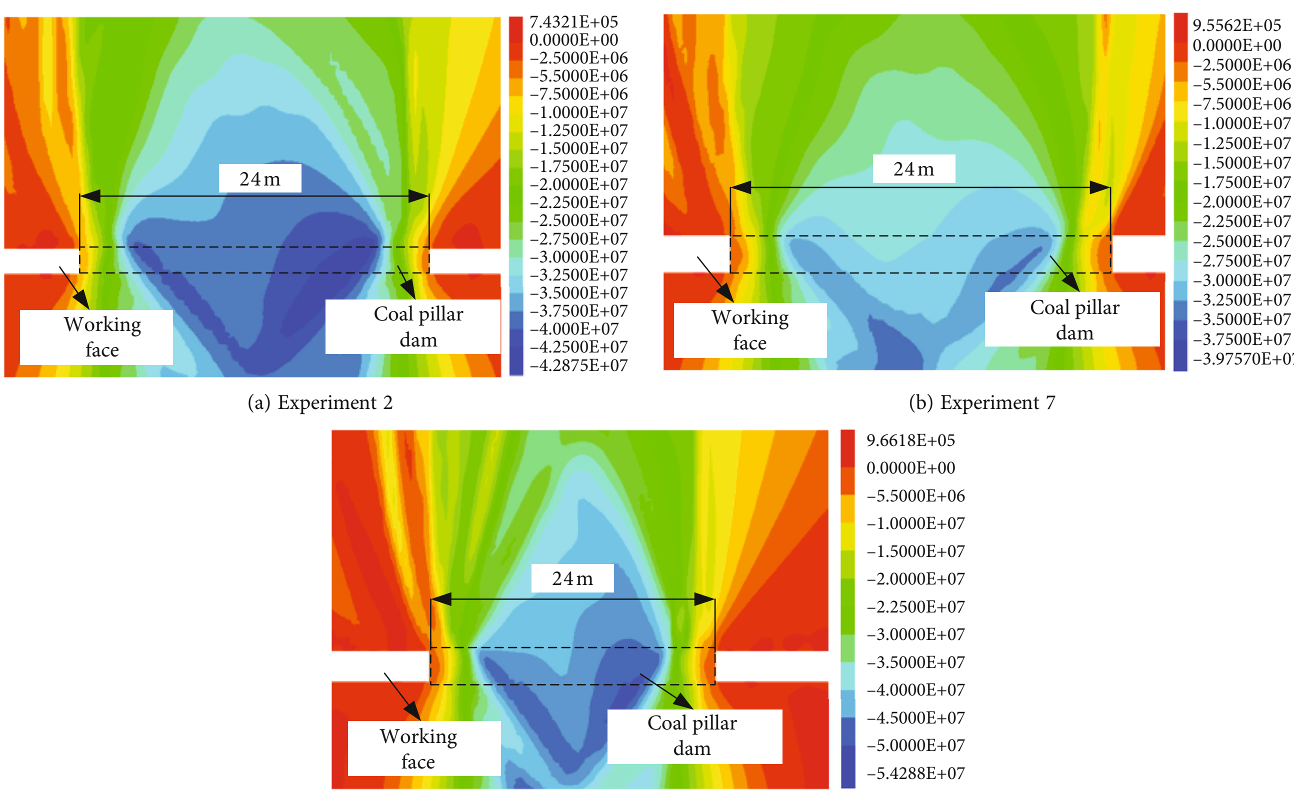
It can be seen from Figures 6–8 that under different mining conditions, the development range and height of the plastic zone on the reservoir side of the coal pillar dam are larger than the working face side, and the horizontal



(a) Experiment 2 (b) Experiment 7

(c) Experiment 14

Figure 6: Plastic zone cloud diagram of partial coal pillar dams.



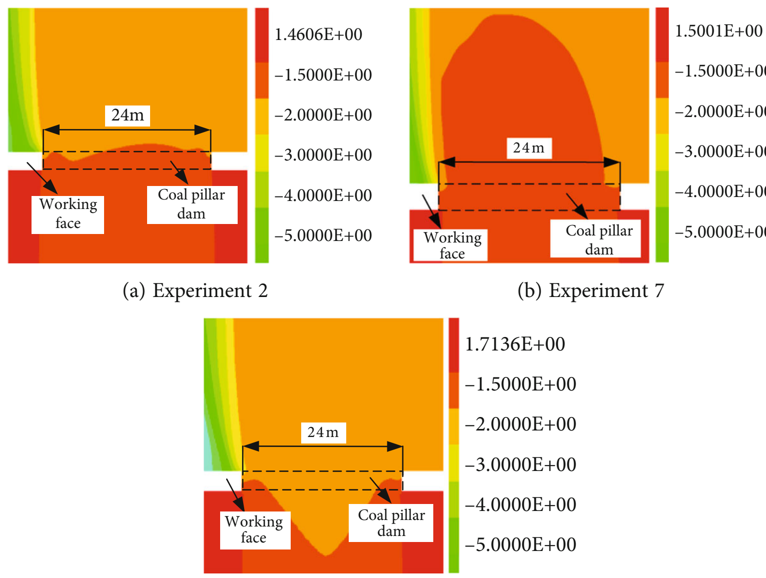
(a) Experiment 2 (b) Experiment 7

(c) Experiment 14

Figure 7: Vertical stress cloud diagram of partial coal pillar dams.

development depth of the plastic zone on the reservoir side is greater about 2~3 m than that on the working face side; the stress concentration area of the coal pillar dam is approximately symmetrically distributed, but the maximum vertical stress is mostly distributed on the working face side; the deformation of the coal pillar dam is divided into upper and lower parts, and the upper deformation is significantly larger than the lower deformation.

By further analyzing the simulation results, the average value of the development height of the plastic zone, the



(a) Experiment 2

(b) Experiment 7

(c) Experiment 14

FIGURE 8: Vertical deformation cloud diagram of partial coal pillar.

TABLE 2: Simulation results.

Test	Development range of the plastic zone/m	Maximum vertical stress/MPa	Vertical deformation/m
1	11.0	45.57	0.63
2	12.0	39.76	0.61
3	15.0	38.21	0.54
4	12.5	36.24	0.53
5	13.5	51.67	0.81
6	12.5	43.06	0.75
7	15.0	42.88	0.82
8	19.0	43.56	0.78
9	18.0	51.16	0.80
10	14.5	53.30	0.72
11	13.5	46.11	1.23
12	16.5	43.61	1.20
13	16.5	58.87	1.05
14	21.0	54.29	1.11
15	19.0	48.93	0.98
16	21.5	41.75	1.25

maximum vertical stress, and the maximum vertical deformation in the coal pillar dam with different levels under the same mining conditions are calculated. The calculation results are shown in Tables 3–5, respectively.

It can be seen from the Tab. that when the inclined length of the working face increases from 100 m to 250 m, the horizontal development range of the plastic zone in the coal pillar dam gradually increases from 12.38 m to 19.50 m, the maximum vertical stress gradually increases from 39.95 MPa to 50.96 MPa, and vertical deformation increases from 0.58 m to 1.07 m. When the width of the coal pillar dam increases from 20 m to 35 m, the horizontal development range of the plastic zone gradually increases from 14.75 m to 17.13 mm, the maximum vertical stress increases from 51.82 MPa to 41.29 MPa, and the vertical deformation increases from 0.77 m to 0.94 m. When the mining height increases from 1.5 m to 3 m, the development height of the plastic zone increases from 14.38 m to 18.25 m and finally reduces to 20.96 m; the maximum vertical stress increases from 44.12 MPa to 47.82 MPa, and the vertical deformation increases from 0.70 m gradually increases to 0.96 m. When the water pressure increases from 0.5 MPa to 2 MPa, the development height of the plastic zone gradually increases from 15.25 m to 16.13 m, the maximum vertical stress increases from 44.85 MPa to 47.08 MPa, and the vertical deformation decreases from 0.92 m to 0.77 m and finally increases to 1.57 m.

In order to more intuitively observe the influence of various factors on the deformation and fracture of the coal pillar dam, the average results in Tables 2–4 were fitted with the horizontal number to obtain the average result trend chart of each factor under different horizontal combinations as shown in Figure 9.

It can be found that different factors have different degrees of influence on the horizontal development range of the coal pillar dam plastic zone, but the effect is the same, and with the increase of inclined length of working face, width of coal pillar, mining height, and water pressure, the horizontal development range of plastic zone of coal pillar dam also increases. Different factors have different effects on the maximum vertical stress inside the coal pillar dam. With the increase of the inclined length of working face, mining height, and water pressure, the maximum vertical stress in the coal pillar dam also increases, and as the width of the coal pillar increases, the maximum vertical stress in the coal pillar dam gradually decreases. This is because the

Table 3: Orthogonal experiment range analysis Tab. (plastic zone development height).

Factor	Length of working face/m	Width of coal pillar/m	Mining height/m	Water pressure/MPa
Average results of the first level	12.38	14.75	14.38	15.25
Average results of the second level	15.00	15.00	14.63	15.50
Average results of the third level	15.63	15.63	15.25	15.88
Average results of the fourth level	19.50	17.13	18.25	16.13
Range	7.13	2.38	3.88	0.88

Table 4: Orthogonal experiment range analysis Tab. (maximum vertical stress).

Factor	Length of working face/m	Width of coal pillar/m	Mining height/m	Water pressure/MPa
Average results of the first level	39.95	51.82	44.12	44.85
Average results of the second level	45.29	47.60	45.99	46.23
Average results of the third level	48.55	44.03	46.81	46.59
Average results of the fourth level	50.96	41.29	47.82	47.08
Range	11.02	10.53	3.70	2.23

Table 5: Orthogonal experiment range analysis Tab. (maximum vertical deformation).

Factor	Length of working face/m	Width of coal pillar/m	Mining height/m	Water pressure/MPa
Average results of the first level	0.58	0.77	0.70	0.92
Average results of the second level	0.79	0.82	0.78	0.91
Average results of the third level	0.99	0.89	0.90	0.83
Average results of the fourth level	1.07	0.94	0.96	0.77
Range	0.50	0.17	0.26	0.15

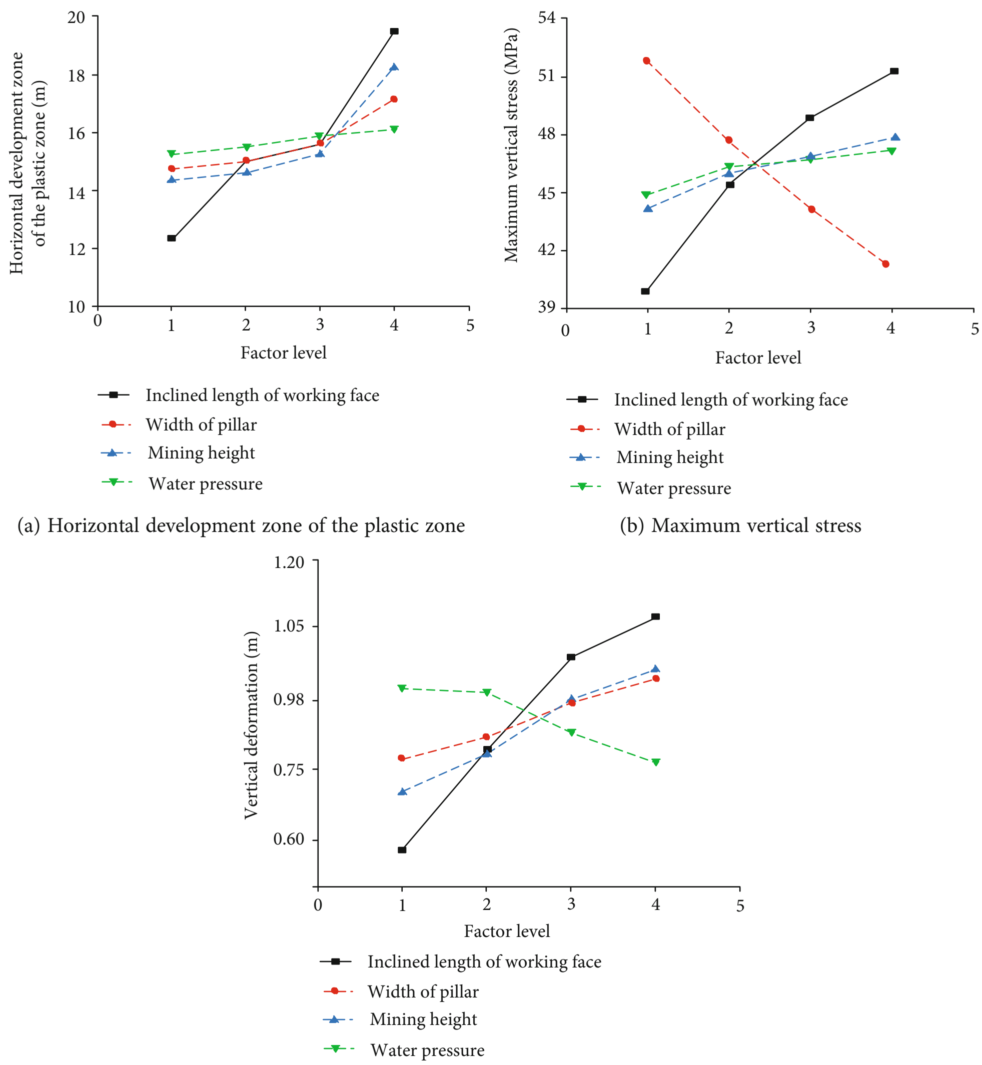
wider the coal pillar is, the better the roof integrity is, the pressure it bears will be reduced, and the stress concentration in the coal pillar will be reduced accordingly. Different factors have different effects on the vertical deformation of the coal pillar dam. With the increase of the inclined length of working face, coal pillar width, and mining height, the vertical deformation of the coal pillar dam gradually increases, and with the increase of water pressure, the vertical deformation of the coal pillar dam gradually decreases, and this is because under the action of the horizontal water pressure, a certain horizontal deformation will occur in the coal pillar, which offsets a part of the vertical deformation, so that the vertical deformation in the coal pillar gradually decreases.

4.3. Significance Analysis of Different Influencing Factors. Perform a range analysis on the orthogonal test results, and calculate the range based on the average of the index results corresponding to each factor and level obtained in Tables 2–4. The calculation results are shown in Tables 2–4.

It can be seen from Table 2 that the range of the four factors by calculating that influence the development height of the plastic zone in the coal pillar dam are 7.13, 2.38, 3.88, and 0.88, respectively, and the sensitivity of the parameters from large to small is the inclined length of working face, mining height, the width of coal pillar, and water pressure. Due to the large range of indicators corresponding to the inclined length of working face, mining height, and the width of pillar, it can be judged that the inclined length of the working face, the mining height, and the width of the coal pillar are the main factors affecting the development of the plastic zone of the coal pillar dam. While the range of the corresponding index of water pressure is relatively small, it can be considered that water pressure is a secondary factor affecting the development of the plastic zone of coal pillar dam.

It can be seen from Table 3 that the range of the four factors by calculating that influence the maximum vertical stress of the coal pillar dam is 11.02, 10.53, 3.70, and 2.23, respectively, and the sensitivity of the parameters from large to small is the inclined length of working face, the width of coal pillar, mining height, and water pressure. Due to the large range of indicators corresponding to the inclined length of working face and the width of pillar, it can be judged that the inclined length of the working face is the main factor affecting the maximum vertical stress of the coal pillar dam. While the range of the corresponding index of mining height and water pressure is relatively small, it can be considered that mining height and water pressure are the secondary factors affecting the maximum vertical stress of the coal pillar dam.

It can be seen from Table 4 that the range of the four factors by calculating that influence the vertical deformation of the coal pillar dam is 0.50, 0.26, 0.17, and 0.15, respectively, and the sensitivity of the parameters from large to small is the inclined length of working face, mining height, the width of coal pillar, and water pressure. Due to the large range of indicators corresponding to the inclined length of working



(a) Horizontal development zone of the plastic zone

(b) Maximum vertical stress

(c) Vertical deformation

Figure 9: Trend chart of average results under different levels of factors.

face and the mining height, it can be judged that the inclined length of the working face and mining height are the main factors affecting the vertical deformation of the coal pillar dam. While the range of the corresponding index of the width of coal pillar and water pressure is relatively small, it can be considered that the width of coal pillar and water pressure are the secondary factors affecting the vertical deformation of the coal pillar dam.

According to the comprehensive range analysis, the range of the three indicators corresponding to the inclined length of the working face is the largest, and it is larger than the range obtained by the other three factors. Therefore, it can be judged that the inclined length of the working face is the main factor affecting deformation and fracture of coal pillar dam, and the width of coal pillar, mining height, and water pressure are the secondary factors affecting deformation and fracture of coal pillar dam.

5. Conclusions

In this study, the fluid-solid coupling calculation model of coal pillar dam affected by mining is established. The long-term immersion of water in coal pillar dam is taken into account. Then, through systematic analysis of the law of deformation and fracture evolution and stress distribution of coal pillar dam under different mining conditions, the main conclusions are as follows:

(1) The development range and degree of plastic zone, the maximum principal stress, and deformation of coal pillar dam increase with the mining process are affected by the mining of adjacent working face. The horizontal development range of plastic zone increases by 23.53%, the maximum vertical stress increases by 95.78%, and the maximum vertical deformation increases by 68.18%. The advance of

working face has the greatest influence on the maximum vertical stress in coal pillar dam and the smallest influence on the horizontal development range of plastic zone

(2) The width of coal pillar, inclined length of working face, mining height, and water pressure all have great influence on the deformation and failure of coal pillar dam. The horizontal development range, the maximum vertical stress, and the maximum vertical deformation of the plastic zone increase continuously with the increase of the inclined length of the working face. The height of plastic zone and the maximum vertical deformation gradually increase, and the maximum vertical stress gradually decreases with the increase of coal pillar width. The horizontal development range, the maximum vertical stress, and the maximum vertical deformation of plastic zone are increasing with the increase of mining height. The horizontal development range and the maximum vertical stress of plastic zone increase, and the maximum vertical deformation decreases gradually with the increase of water pressure

(3) The influence of the different factors on the deformation and failure of coal pillar dam is different. Through the analysis of the range of the simulation results, it is found that the inclined length of the working face is the main factor affecting the development of the plastic zone of the coal pillar dam, the width of the coal pillar, and the mining height. The inclined length of working face and the width of coal pillar are the main factors affecting the maximum vertical stress of coal pillar dam. The inclined length and mining height of working face are the main factors affecting the maximum vertical deformation of coal pillar dam

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 there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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