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Research Article

Research on a Numerical Simulation and Prediction Model of Floor Mining Failure Depth in the Chenghe Mining Area

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Ordovician limestone water on the floor is a serious threat to the safety of coal mine production in the Weibei coalfield, and prediction of the floor failure depth is the key for evaluating the mining conditions under pressure. This paper combines the hydrogeological conditions of the no. 5 coal seam and uses the FLAC3D program to determine the floor failure depth under two-factor (mining depth and width) and multifactor (mining depth, width, and height) conditions via numerical calculations and analysis. We obtain the fitting formula for the floor failure depth and analyze the influence of various factors on it. The results show that when the mining width does not exceed 200 m, the mining width has the greatest influence on the floor failure depth, followed by mining depth and mining height. In this paper, the working face floor failure depths measured values of 18 flat seams in China are taken as samples for comparison with the values calculated via empirical formulas and fitting formulas, and the maximum and minimum absolute errors and relative errors are analyzed. The nonlinear fitting regression formulas offered in this paper are found to provide strong predictive value, high accuracy, and a relatively small error range. The reliability and rationality of the models are further verified, thus providing a reference for future mining operations under safe aquifer water pressure conditions in the Weibei coalfield.

1. Introduction

With the gradual depletion of mining resources in shallow coal seams in China, the mining depth has gradually increased. Coal mine water disasters are a problem faced by most deep mines in China, and they seriously restrict the safe and efficient production of mines. Due to the complex geological structure in China, water inrush from the coal seam floor is often hidden and sudden. According to incomplete statistics, since 1955, there have been more than 2000 floor water inrush accidents in China, including more than 220 flooded shafts, causing more than 8000 casualties and hundreds of billions of yuan in economic losses [1].

Two methods are mainly used to avert water inrush from the coal seam floor. The first method is to depressurize the aquifer by releasing large amounts of confined water. However, this method causes pollution and waste of groundwater resources in the surrounding areas. The other method makes full use of the self-characteristics of the floor aquifuge to prevent the confined water from bursting into the working face or goaf [2]. When the support pressure from coal seam mining exceeds the ultimate strength of the floor rock mass, the floor will produce a failure zone with a certain depth [3, 4], which reduces the thickness of the effective aquifuge and increases the risk of water inrush. Therefore, determining the floor failure range is the key to preventing and controlling mine water disasters.

In recent years, with the development of simulation technology, many scholars have carried out simulation research on the floor failure law. For example, Meng et al. [5] took a working face as the research object and performed numerical simulations of floor failure of the inclined coal seam with FLAC3D software. They found that the range of plastic failure was consistent whether along the inclined direction or along the strike direction. Zhu et al. [6] took a mine as an example and studied the change laws of the strain as the working face advanced and the distribution characteristics of the floor plastic zone at different depths through both numerical simulation and experimentation. Liu et al. [7] used FLAC3D numerical simulation software to find that the floor plastic failure depth increases to a certain value with increasing coal seam tilt and then decreases. In addition, many scholars have measured the floor failure depth in coal mining faces, which are troubled by water disasters in China. For example, Li and Bai [8] took the F6106 working face of the Inner Mongolia Buliangou coal mine as the test site and analyzed the coal seam floor mining failure law using coal mine floor water injection testing, rock strain detection, and theoretical analysis, and the field detection results were consistent with the theoretically predicted results. Kong et al. [9] arranged an optical fiber sensor detection system and a resistivity CT detection system in the drill hole and precisely detected the floor failure depth in the working face under mining conditions. Zhao [10] taking the 11913 isolated coal mining face in the Gequan coal mine of Hebei Province as the research object used the KJ959 coal mine microseismic monitoring system to detect the floor failure depth.

Both the numerical simulation method and the field measurement method can obtain the floor failure depth of the floor only for individual coal mines and require a great deal of manpower and time. Most coal mining operators in China are willing to adopt relatively simple and rapid empirical formula methods. However, due to the great difference in hydrogeological conditions in different mining areas in China, the empirical formula in the regulations cannot be applied to all mining areas. Scholars have put forward various empirical formulas suitable for the mining area in view of the hydrogeological conditions of a certain mining area [11–13], but for the floor failure law of the Chenghe mining area in the Weibei coalfield, there are no targeted analysis and no empirical formula that can be used for reference. Thus, this study combined the hydrogeological conditions of the no. 5 coal seam and uses FLAC3D to determine the disturbance and floor failure depth under different conditions. The influence of each factor on the floor failure depth was determined, and the formulas for the calculation of the floor failure depth in Chenghe were obtained. This paper provides a reference for future mining operations under safe aquifer water pressure conditions in the Chenghe mining area and the Weibei coalfield.

2. Study Area and Hydrogeological Conditions

The Chenghe mining area, which is located in Shaanxi Province, China, in the eastern part of the Weibei coalfield. The strata from old to new are as follows: Ordovician, Carboniferous, Permian, Triassic, Cenozoic, Tertiary, and Quaternary. There are 11 coal seams in total, and the total thickness is 8.72 m; only the no. 5 coal seam is fully minable. Figure 1 shows the geographical location and the comprehensive stratigraphic column map of the Chenghe mining area in Weibei.

The total thickness of the Ordovician limestone aquifer exceeds 500 m. The water in the aquifer is mainly supplied by the infiltration of atmospheric precipitation, the leakage of rivers flowing through the limestone outcrops, and the leakage of reservoirs built in the limestone-exposed area. The Fengfeng formation is the direct basement of the coal measure strata; it is composed of dolomite and dolomitic limestone with limestone, with developed corrosion fissures and strong water abundance. The unit inflow of the borehole is 0.2–1.5 L/s·m. The upper part of the Ordovician limestone aquifer is approximately 30 m from the coal floor, and the aquifuge is thin, which seriously threatens the safe operation of the mine.

3. Methods

This study takes the no. 5 coal floor in the Chenghe mining area as the research object and uses FLAC3D to simulate the mining failure characteristics of the floor through a variety of factors, as influenced by the no. 5 coal seam floor rock mass mining failure characteristic study, to build a reasonable calculation model. After more than ten years of research on the coal seam floor failure law in the Chenghe mining area, it is found that with increasing mining depth and width, the support pressure around the mining face and the floor failure depth increase. Therefore, for this model, it is necessary to highlight the influence of mining width and burial depth on floor failure. In the numerical simulation analysis of the floor deformation and failure characteristics, it is necessary to combine rock strata with slight differences in physical properties into a single layer. According to the actual geological conditions of the roof and floor of the no. 5 coal seam, the strata are divided into 14 groups of model materials [14], as shown in Figure 2. Table 1 shows the specific mechanical parameters of each layer.

Combined with the stratum situation of the Chenghe mining area and the mining situation of no. 5 coal, the floor maximum failure depths of working faces with different mining depths and mining widths were calculated.

As shown in Figure 3, the numerical calculation model is 90 m high in the Z-direction, 300 m long in the Y-direction, and 400 m wide in the X-direction, with a total of 432,000 elements and 455,182 nodes. The coal seam is nearly horizontal, and the distance between the open-off cut hole and the model boundary is 70 m. In the model, the top interfaces are set as stress boundaries, and all other interfaces are set as displacement boundaries. The bottom and vertical interfaces are set as sliding supports. To simulate the load of the upper stratum, according to the different burial depths, a compressive stress (Q) of 0.9–10.8 MPa is applied on the top interface. The bottom of the aquifuge is subjected to a vertical upward water pressure of 1.4 MPa. According to the characteristics of underground mining, the large area is assigned to the elastic rock mass, which can be approximated as an elastic model, and the local area is assigned to plastic yield failure, which can be treated as an elastic-plastic model. In this study, the failure of rock mass in the model follows the Mohr-Coulomb yield criterion, and the stress, displacement, and

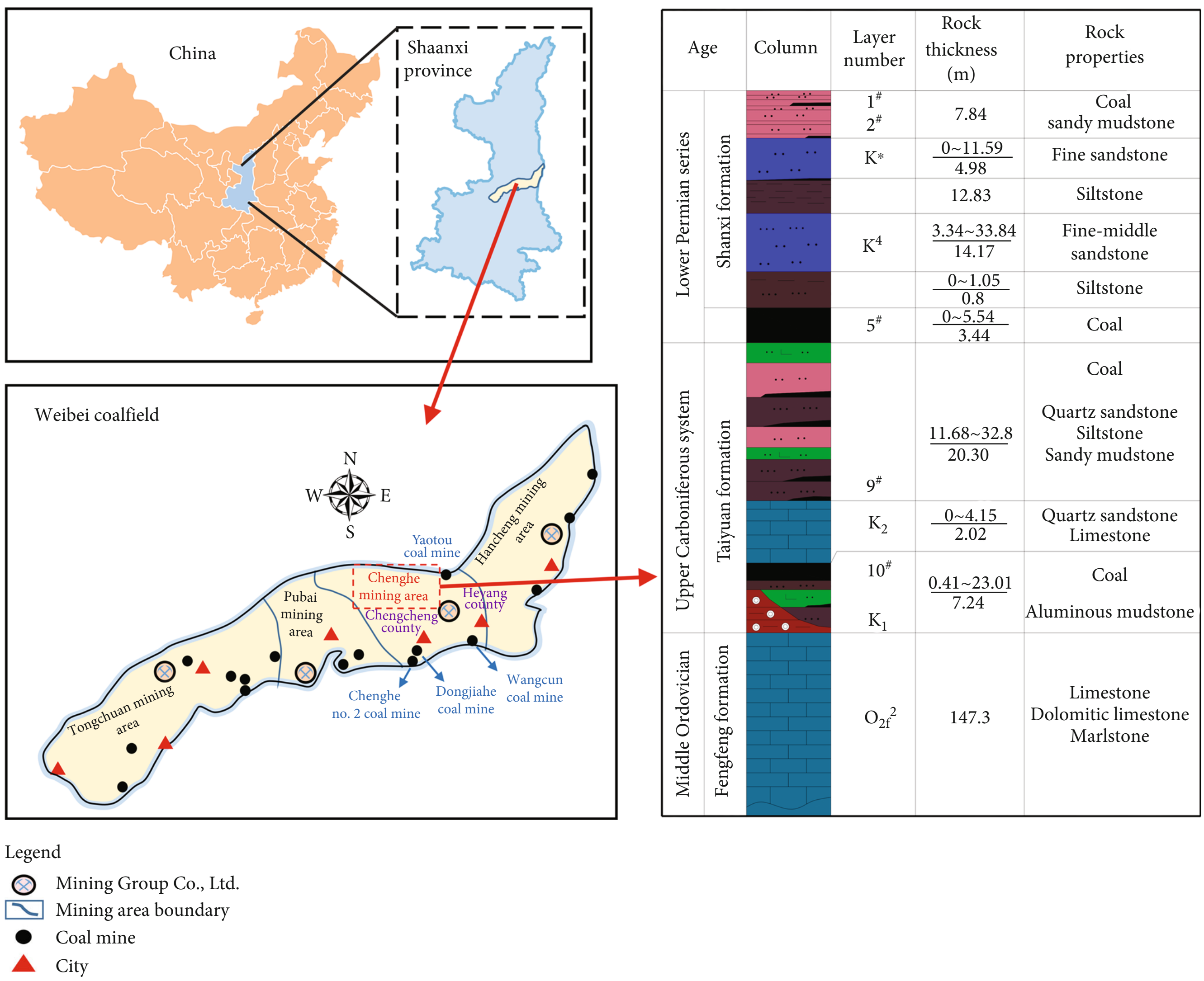


Figure 1: Geographical location and comprehensive stratigraphic column map of the Chenghe mining area.

failure are simulated when the working face reaches equilibrium. The rock stratum is a continuous medium, and plastic flow is not considered.

As shown in Figure 4, excavation calculation can be carried out only after all nodes and elements are balanced. The stress balance mainly observes the stress in the vertical direction. The whole model is excavated in 30 steps of 5 m each, for a total of 150 m. After all excavation is completed, the maximum failure depth of the floor is determined.

4. Results and Discussion

4.1. Two-Factor Floor Failure Depth Prediction Model. To study the influencing factors of the coal seam floor failure depth, the mining width and the burial depth of the no. 5 coal seam are changed under the conditions of a 28 m floor aquifuge thickness and a 1.4 MPa confined water pressure. Figures 5–9 show the floor failure range with different burial depths under the same mining width.

According to the simulation results, it is found that the floor failure depth increases nonlinearly with increasing mining face width when the coal seam depth is fixed, but when the mining width increases to 140 m, the failure degree of the roof and floor increases greatly. When the width is increased to 160 m, the increase in the floor failure depth is not obvious compared with that at 140 m, but the height and scope of roof failure and the extent of floor rock failure at 160 m are significantly increased compared with those at 140 m. According to the above numerical simulation test scheme, the calculated floor failure depth is shown in Table 2.

According to the different results in Table 2, the numerical simulation fitting formula of the floor failure depth under the condition of a 4.0 m mining height can be obtained by using the mathematical statistics method.

$$h = 0.0117H + 6.25 \ln \frac{L_x}{40} + 0.54, \quad (1)$$

where h is the maximum floor failure depth (in m), H is the burial depth (in m), and L_x is the working face width (in m).

The following can be seen from fitting formula (1):

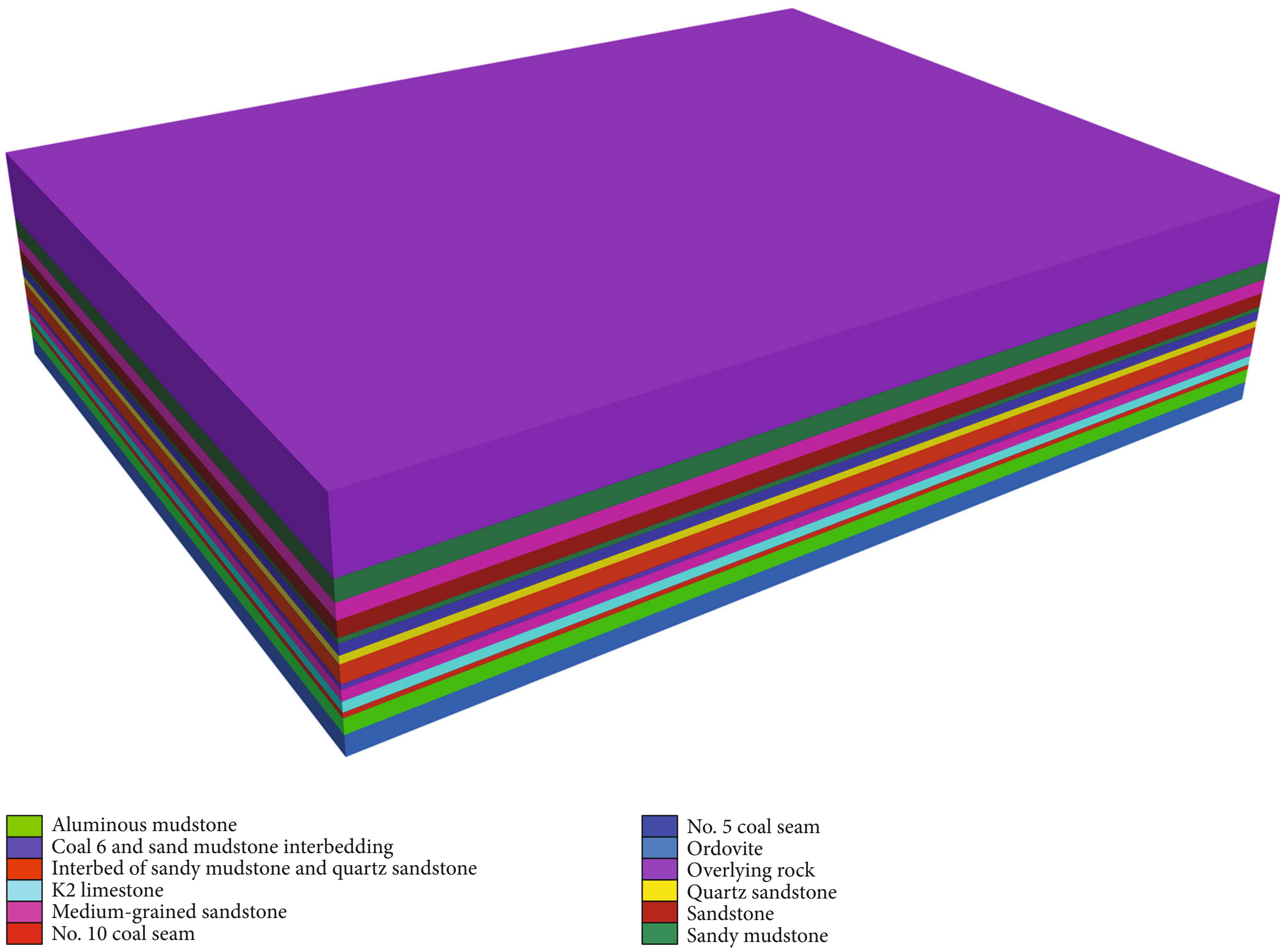


Figure 2: Geological model map.

Table 1: List of rock mass parameters.

Lithology	Thickness (m)	Cumulative thickness (m)	Bulk modulus (GPa)	Shear modulus (GPa)	Density ($kg{\cdot}m^{-3}$)	Cohesion (MPa)	Internal friction angle (°)	Tensile strength (MPa)
Overlying rock	28	28	4.67	4.34	2670	4.67	39	1.34
Sandy mudstone	8	36	3.65	3.28	2640	2.25	38	1.55
Medium-grained sandstone	6	42	3.38	3.32	2650	5.00	40	1.10
Sandstone	6	48	4.22	4.03	2620	3.98	39	1.11
Sandy mudstone	2	50	3.65	3.28	2640	2.25	38	1.55
No. 5 coal seam	4	54	1.43	0.44	1400	1.52	28	0.10
Quartz sandstone	3	57	4.54	4.31	2660	4.72	40	1.21
Interbedding of sandy mudstone and quartz sandstone	7	64	4.20	4.15	2640	4.58	39	1.24
No. 6 coal seam and sandy mudstone interbeds	2	66	3.65	3.28	2640	2.25	38	1.55
Medium-grained sandstone	4	70	3.38	3.32	2650	5.00	40	1.10
K2 limestone	4	74	22.6	11.1	2090	3.65	37	1.71
No. 10 coal seam	2	76	1.43	0.44	1400	1.00	25	0.10
Aluminous mudstone	6	82	4.86	4.78	2620	4.71	30	1.51
Ordovician limestone	8	90	8.78	5.23	2770	4.32	37	1.32

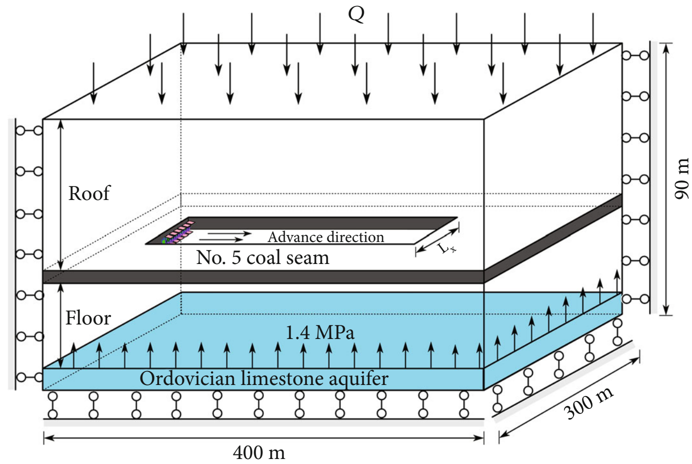


FIGURE 3: Model boundary conditions and the excavation of the coal seam position.

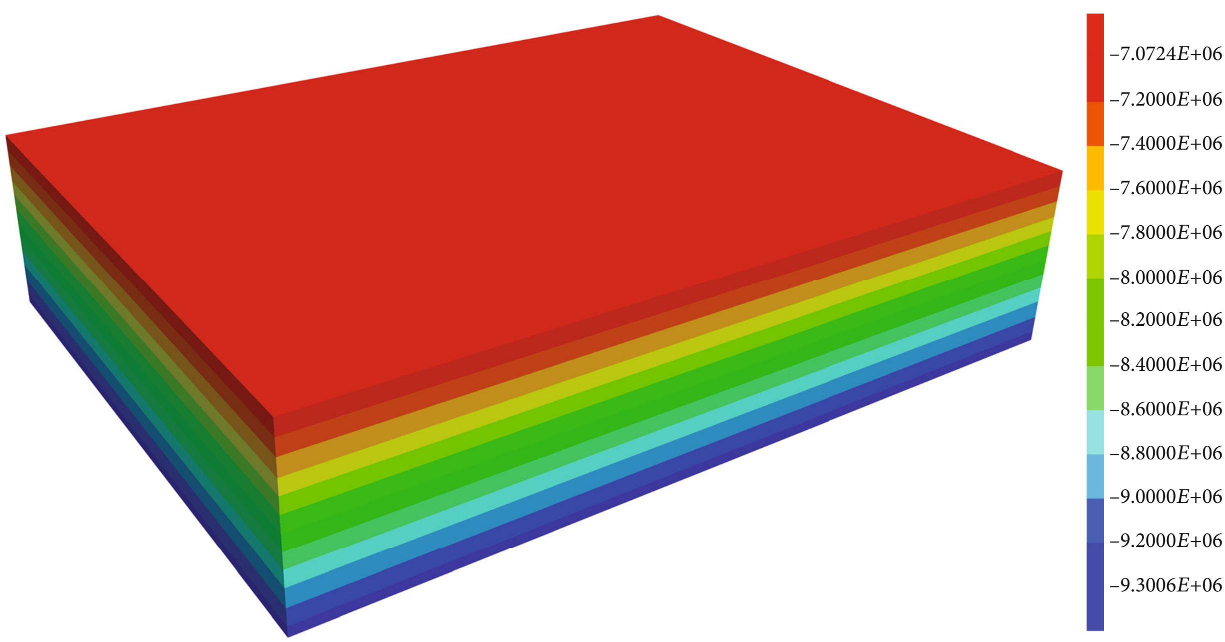


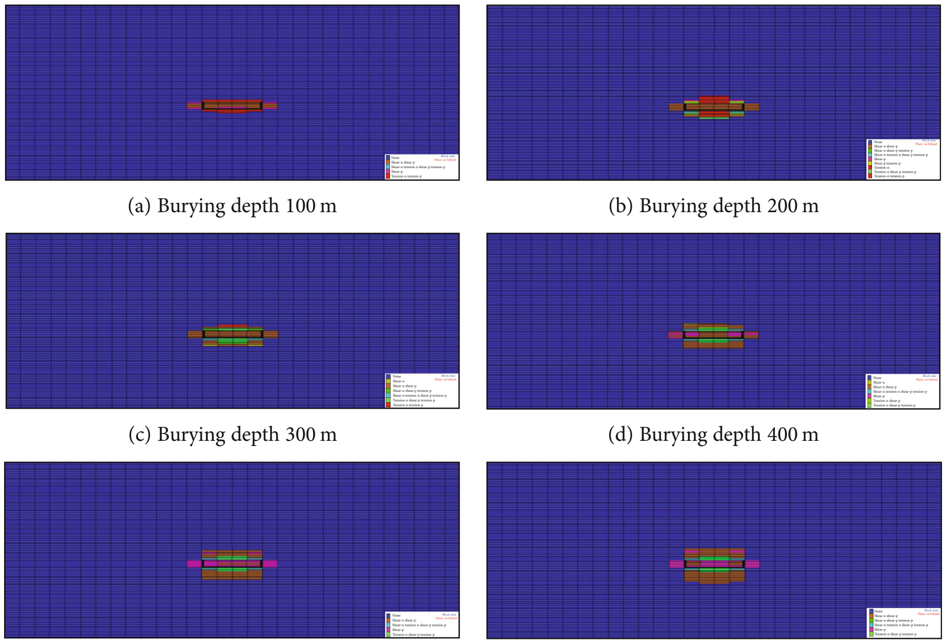
FIGURE 4: Vertical stress distribution map.

(1) The floor failure depth increases with increasing working face width, but when the working face width exceeds a certain range, the change in floor failure depth is not obvious, and it changes only in terms of the width and extent of the rupture. This is consistent with the in situ measurement results: the larger the inclined length, the deeper the floor failure depth, but beyond a certain range, the influence of the inclined length on the floor failure depth is small

(2) When the working face width is narrow, the coal seam burial depth has little effect on the floor failure depth, mainly because, when the mining width is narrow and small, the overlying roof strata show a more regular "three-zone" failure mode, but when the working face is widened to a certain width, the influence of the coal seam burial depth on the floor failure depth increases linearly

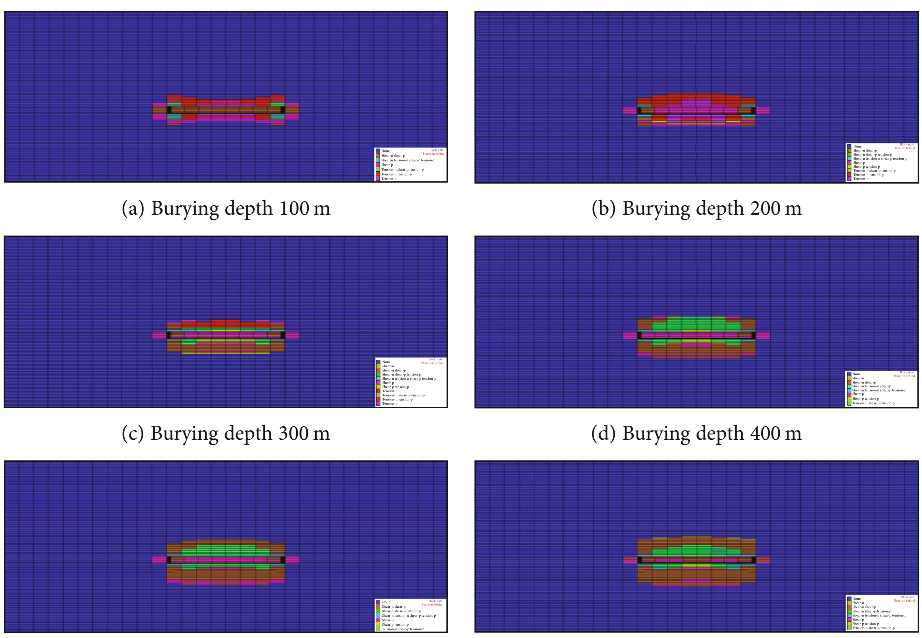
(3) It can be clearly seen from the contrast diagram of the difference between the fitting value and the simulated value of the prediction model of floor failure depth (Figure 10) that data points with large deviation mainly concentrate on working face widths of 20 m, 180 m, and 200 m, while the actual working face width is generally in the range from 120 to 160 m. Therefore, the regression fitting model proposed in this paper offers high precision, and the correlation coefficient of the prediction model reaches 0.93, which can meet the needs of engineering applications

(4) Figure 11 shows the analysis curves of the influences of the mining depth and working face width on the floor failure depth. This figure reveals that the sensitivity degree of the floor disturbance failure depth to



(a) Burying depth 100 m
(b) Burying depth 200 m
(c) Burying depth 300 m
(d) Burying depth 400 m
(e) Burying depth 500 m
(f) Burying depth 600 m

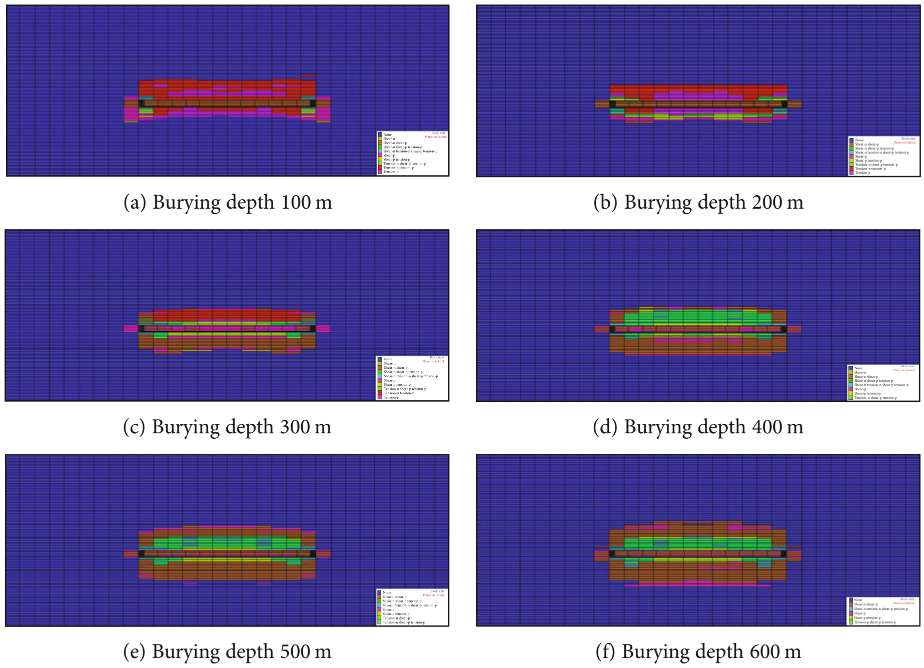
Figure 5: Floor failure range with different burial depths under the working face width of 40 m.



(a) Burying depth 100 m
(b) Burying depth 200 m
(c) Burying depth 300 m
(d) Burying depth 400 m
(e) Burying depth 500 m
(f) Burying depth 600 m

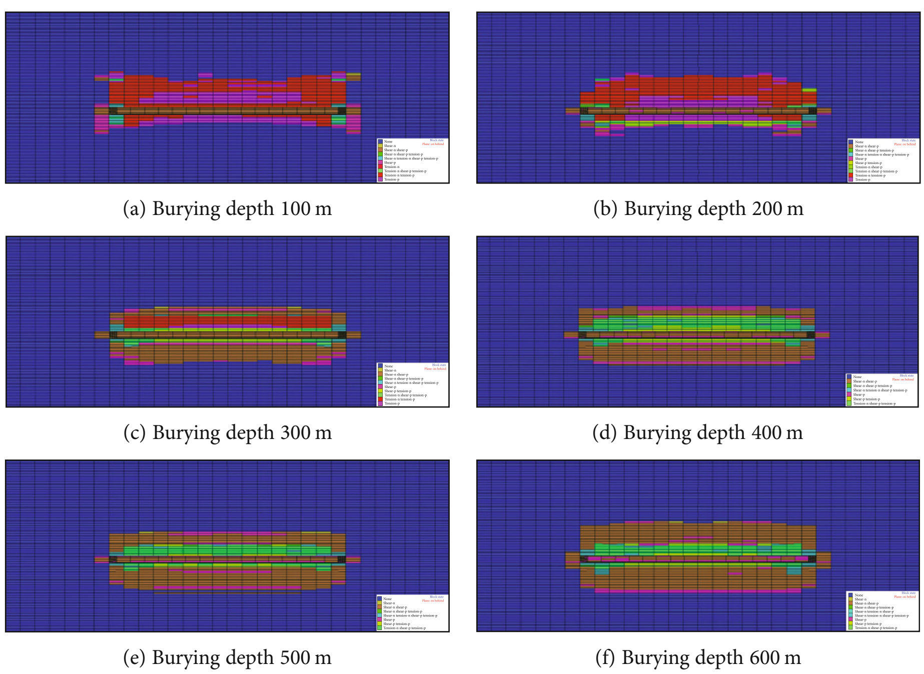
Figure 6: Floor failure range with different burial depths under the working face width of 80 m.

the mining depth is greater than that to the mining width. The floor failure depth values of various factors at different levels are compared, and the following results are obtained. (a) The burial depth has a linear relationship with the failure depth, and the slope of the curve is large. With the monotonic increase in the mining depth, the floor failure depth is deepened. The intrinsic mechanism of this trend change is mainly influenced by the in situ stress. With the increase in burial depth, the abutment pressure and its peak value of the coal and rock mass around the goaf increase, which agrees with the actual situation of the evolution of floor failure depth. (b) The relationship between the floor failure depth and the mining width can be determined via logarithmic regression, and as the mining width increases, the floor failure depth deepens and the curve changes greatly, but the slope of the fitting curve decreases



(a) Burying depth 100 m (b) Burying depth 200 m (c) Burying depth 300 m (d) Burying depth 400 m (e) Burying depth 500 m (f) Burying depth 600 m

Figure 7: Floor failure range with different burial depths under the working face width of 120 m.

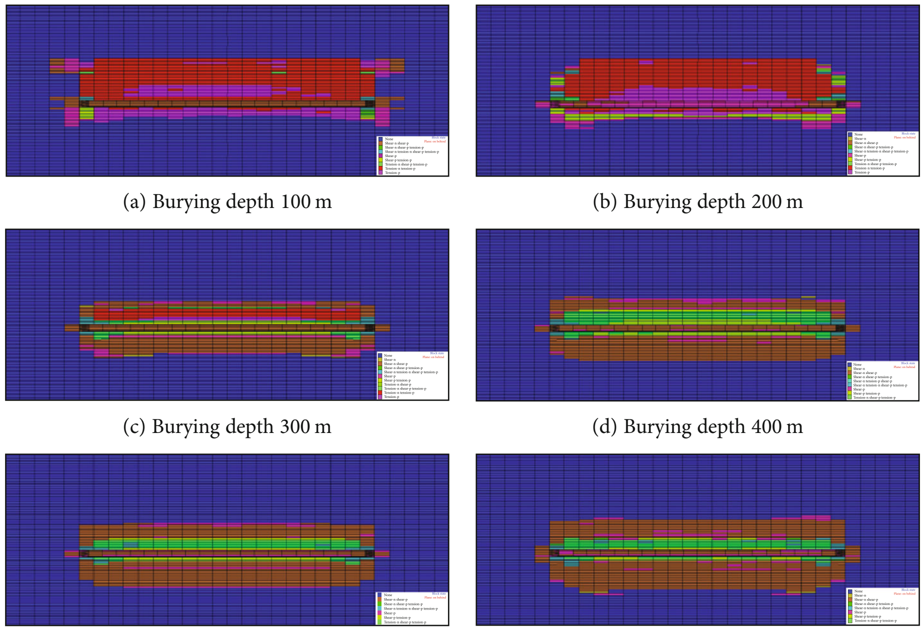


(a) Burying depth 100 m (b) Burying depth 200 m (c) Burying depth 300 m (d) Burying depth 400 m (e) Burying depth 500 m (f) Burying depth 600 m

Figure 8: Floor failure range with different burial depths under the working face width of 160 m.

continuously. When the working face increases to a certain width, the sensitivity of the floor failure depth to the mining width decreases and eventually stabilizes. This variation in the curve conforms to the values measured in situ and the collective experiences of mine floor failures in Weibei and throughout China. In general, the regression fitting equation proposed in this paper confirms the feasibility of the numerical simulation test results

4.2. Multifactor Floor Failure Depth Prediction Model. According to previous results of in situ measurements, when the burial depth is less than 400 m, the floor failure is essentially unaffected by the mining height [15]. After entering deep mining, the floor failure degree is more affected by the mining height. If the influence of mining height is not considered, the calculated depth of the prediction formula and the actual depth produce a larger error, which will be detrimental to the prevention and control of floor water hazards [16].



(a) Burying depth 100 m (b) Burying depth 200 m

(c) Burying depth 300 m (d) Burying depth 400 m

(e) Burying depth 500 m (f) Burying depth 600 m

Figure 9: Floor failure range with different burial depths under the working face width of 200 m.

Table 2: Simulation results of floor failure depth under different conditions.

		Working face width (m)									
		20	40	60	80	100	120	140	160	180	200
		Numerical simulation results of floor failure depth (m)									
	100	0.0	1.7	4.2	6.0	7.4	8.6	9.5	10.4	11.1	11.8
	150	0.0	2.3	4.8	6.6	8.0	9.2	10.1	10.8	11.1	11.3
	200	0.0	2.9	5.4	7.2	8.6	9.7	10.7	11.2	11.3	11.9
	250	0.0	3.5	6.0	7.8	9.2	10.3	11.3	12.1	12.9	13.5
	300	0.0	4.0	6.6	8.4	9.8	10.9	11.9	12.7	12.9	13.1
Burial depth of seam no. 5 (m)	350	0.3	4.6	7.2	9.0	10.4	11.5	12.5	12.7	12.8	12.9
	400	0.9	5.2	7.7	9.5	10.9	12.1	13.0	13.2	13.6	14.1
	450	1.5	5.8	8.3	10.1	11.5	12.7	13.6	13.8	13.9	13.9
	500	2.1	6.4	8.9	10.7	12.1	13.3	14.2	14.5	14.8	15.4
	550	2.6	7.0	9.5	11.3	12.7	13.8	14.8	15.1	15.4	15.6
	600	3.2	7.6	10.1	11.9	13.3	14.4	15.4	15.5	15.8	15.8
	650	3.8	8.1	10.7	12.5	13.9	15.0	16.0	16.5	16.6	16.8

In the previous section, the simulation results and fitting formula (1) under different mining depths and widths are given, but the formula is based on a coal seam thickness of 4.0 m without considering the influence of other coal seam thicknesses, which will lead to deviations in the predictions. Therefore, based on the parameters given in Table 1, this paper establishes numerical calculation models for coal seam thicknesses of 2.0 m and 3.0 m. Due to space limitations, the detailed simulation results are not given here. By using FLAC3D, the floor failure depth in several working faces under different conditions in the no. 5 coal seam is simulated and calculated. The fitting formula of a multifactor model for the numerical simulation calculation of the floor failure depth is obtained by using mathematical and statistical methods.

$$h = 0.0117H + 6.25 \ln \frac{L_x}{40} + 0.081M + 0.236, \qquad (2)$$

Here, M is the mining height of the coal seam (in m), and other parameters are as defined above.

4.3. Model Reliability Verification. To check the reliability of the model, the floor failure depth was measured on the 13506 mining face in the Wangcun coal mine of the Chenghe mining area.

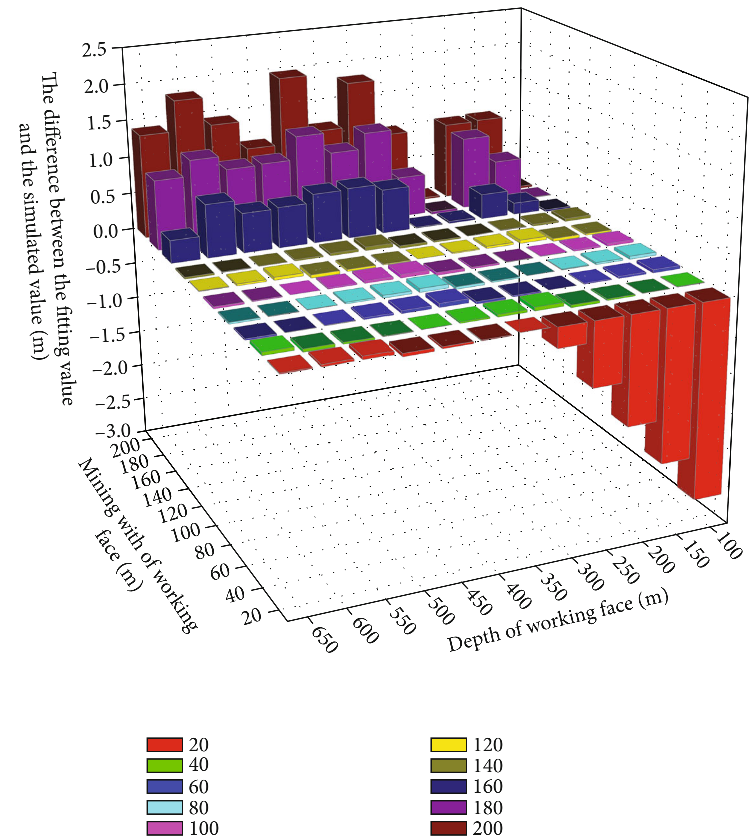
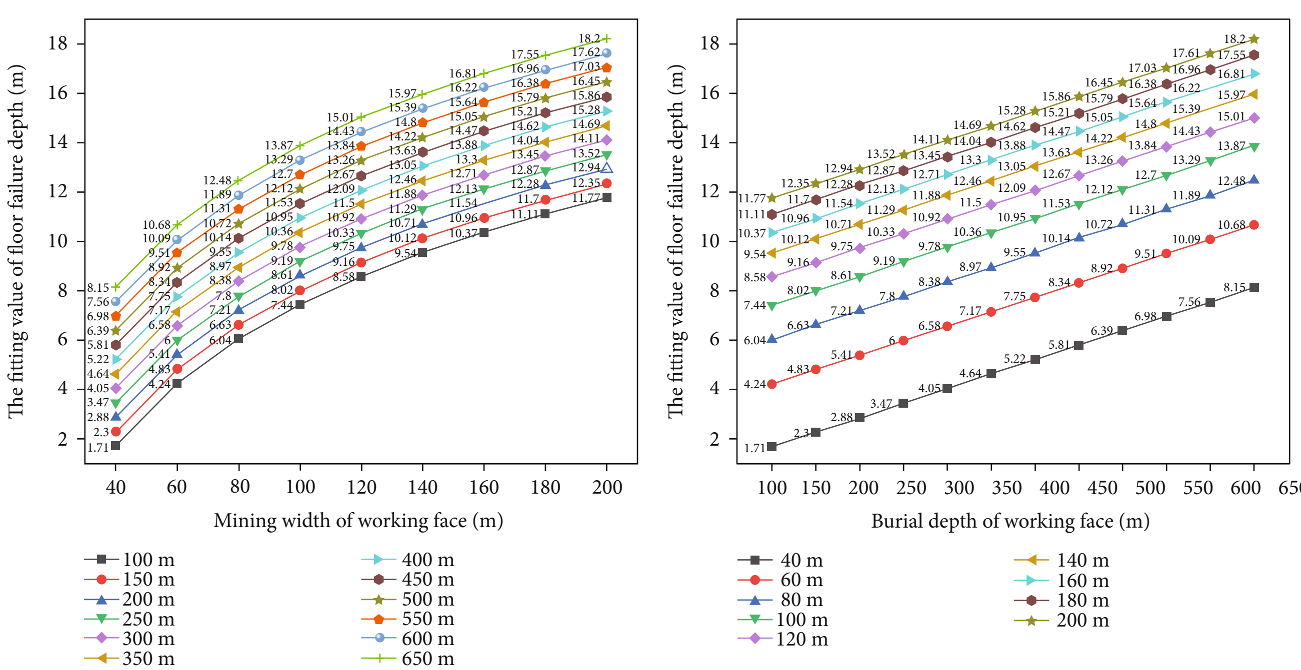


Figure 10: Contrast map of the difference between the fitting value and the simulated value of the floor failure depth prediction model.



(a)

(b)

Figure 11: Analysis curve of the influence of mining depth and mining width on the floor failure depth: (a) the relationship curve between the floor failure depth and the mining width of the working face and (b) the relationship curve between the floor failure depth and the working face depth.

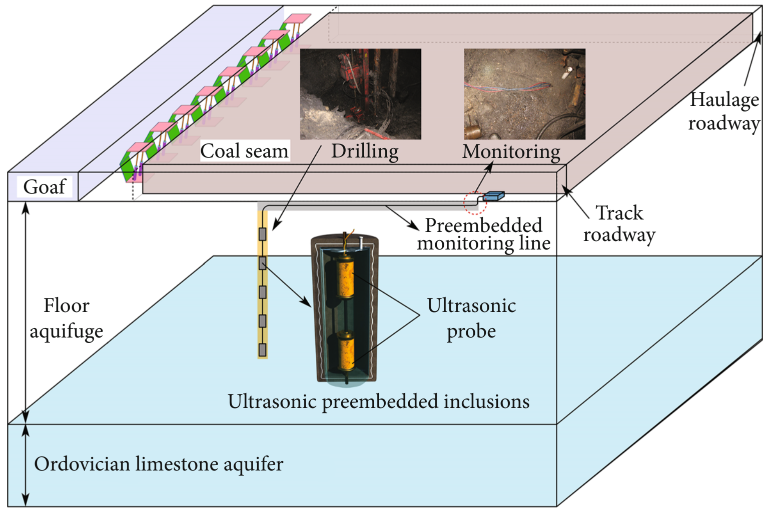


Figure 12: Site layout and test drawing.

The strike length of the 13506 mining face is 1050 m, the width is 125 m, and the average burial depth is 220 m. The average thickness of the coal seam is 2.2 m, which indicates a medium-thick coal seam. The average dip angle of the coal seam is 8°, which indicates a gently inclined coal seam. There are 1–3 layers of gangue in the coal seam, which indicates a coal seam with complex structure. The working face is arranged according to the strike longwall, adopting the single-strike longwall backward-type full-caving mining method.

In the field, the test method of drilling ultrasonic preembedded inclusions is used to measure the floor failure depth. In principle, during coal mining, the floor is affected by mining, and the stress state of each measuring point in the floor rock mass changes accordingly. Compared with the change law of the ultrasonic propagation velocity, the floor failure depth after mining can be obtained. According to the actual situation of the site, a vertical borehole with a depth of 18 m is arranged in the track roadway. When the mining face is advanced 90 m from the borehole, the test is initiated, as illustrated in Figure 12.

According to the test results, when the vertical depth is within 3–11.35 m, the floor rock mass undergoes plastic damage. The cracks of the floor rock strata increase, the time of ultrasonic wave propagation increases obviously, and the waveform fluctuates greatly. When the vertical depth is 11.35–18 m, the fluctuation in the acoustic wave is yet not obvious. Thus, the influence of mining on this test section is not obvious, and cracks have not yet developed. Therefore, the test results of ultrasonic preembedded inclusions show that the maximum floor failure depth of the 13506 working face is 11.35 m, which is consistent with the predicted values of 11.41 m and 11.28 m for the floor failure depth calculated by fitting formulas (1) and (2).

4.4. Applicability Analysis of the Models. The above analysis reveals that the correlation coefficients of the prediction models are all greater than 0.9. The regression curve in this paper has a high degree of fitting to the failure depth data obtained by the numerical simulation. However, whether the fitting formulas are feasible for practical applications in other mines remains to be determined. The following is a verification and comparative analysis of the value of the working face floor failure depth of flat seams (the inclination is less than 15 degrees) measured in situ in the Chenghe mining area in Weibei, the Hancheng mining area in Weibei, other mining areas in the country, and the prediction model. To obtain a better comparative effect, the empirical fitting formulas (formulas (3), (4) and (5)) in the regulations are selected for comparative calculation and analysis. The results are shown in Tables 3 and 4 [17].

$$h = 0.7007 + 0.1079L_x, \tag{3}$$

$$h = 0.303{L_x}^{0.8}, \tag{4}$$

$$h = 0.0085H + 0.1665\alpha + 0.1079L_x - 4.3579, \tag{5}$$

Here, α is the inclination of the working face (in °), and other parameters are as defined above.

As shown in Tables 3 and 4, the calculated average value and error of the floor failure depth of nonlinear regression fitting formulas (1) and (2) given in this paper are all less than the values of formulas (3), (4), and (5) by the regulations. This result shows that the regression equation of the numerical simulation given in this paper is closer to the values measured in situ than those of the three prediction formulas of floor failure depth given in the regulations, and the accuracy is higher than the predicted values obtained using the regulations.

When predicting the floor failure depth, if the predicted value is higher than the value measured in situ, the thickness of the effective floor aquifuge is reduced, the grouting amount is insufficient, and the mining safety factor is reduced, leading to a decreased exploitable area and an increased dangerous mining area, which is not conducive to the rational utilization of coal resources. If the predicted value is lower than the value measured in situ, the floor effective aquifuge thickness will increase and the floor grouting quantity will increase, which will increase mining costs. In Tables 3 and 4, the calculation results of the three prediction

Table 3: Comparison of in situ values and fitting values of the working face floor failure depth in different mining areas.

Serial number	Name of the working face	In situ measured value of floor failure depth (m)	Fitting values in formula (1)	Fitting values in formula (2)	Empirical value in formula (3)	Empirical value in formula (4)	Empirical value in formula (5)
1	1100 working face of the Magouliang coal mine in Hancheng	13.00	10.10	9.98	13.65	13.96	10.57
2	1208 working face of the Shuanggou coal mine in Zibo	9.50	11.26	11.04	14.73	14.88	12.14
3	4707 big working face of the Jingxing no. 1 coal mine	6.50	5.96	5.98	5.56	6.37	3.92
4	32031(1) working face of the Wucun coal mine	9.70	8.43	8.32	8.25	9.07	6.42
5	3305 working face of the Wucun coal mine	11.70	13.65	11.12	13.65	13.96	11.40
6	1204 working face of the Shuanggou coal mine in Zibo	10.50	12.81	12.58	17.96	17.57	15.55
7	7607 narrow working face of the Xingtai coal mine	9.70	6.82	6.95	7.17	8.02	4.85
8	7607 wide working face of the Xingtai coal mine	11.70	10.01	10.14	11.49	12.06	9.16
9	11-014 working face of the Caocun coal mine	8.50	8.61	8.43	11.49	12.06	8.16
10	7406 working face of the Baizhuang coal mine in Feicheng	9.75	10.54	10.39	14.73	14.88	11.62
11	22510 working face of the Chenghe no. 2 coal mine	10.00	9.78	9.62	11.49	12.06	9.01
12	4707 s-1 working face of the Jingxing no. 1 coal mine	8.00	4.20	4.51	4.37	5.09	2.74
13	4707 s-2 working face of the Jingxing no. 1 coal mine	6.00	4.20	4.22	4.37	5.09	2.74
14	5701(1) working face of the Jingxing no. 3 coal mine	3.50	1.40	1.38	3.94	4.60	0.84
15	13506 working face of the Wangcun coal mine	11.35	11.41	11.28	14.19	14.42	11.87
16	5206 working face of the inclined shaft in the Wangcun coal mine	13.87	12.12	12.00	16.89	16.68	14.25
17	24508 working face of the Chenghe no. 2 coal mine	8.30	7.75	7.77	7.17	8.02	5.52
18	22507 working face of the Dongjiahe coal mine	10.75	10.48	10.45	13.00	13.40	10.41

formulas in the regulations are either too large or too small, which is not conducive to the safe mining and effective utilization of the working face. Fitting formulas (1) and (2) of the new prediction model are more advantageous to the safe and rational mining of coal working faces.

The comparison results between the values measured in situ and the fitted values of the floor failure depths of the mining faces in different mining areas are shown in Table 5. The maximum absolute error, the minimum absolute error, the maximum relative error, and the minimum relative error of the floor failure depth calculated by formulas (1) and (2) are 3.8, 0.06, 60.65%, and 0.53%, respectively. The maximum absolute errors in the three empirical formulas adopted in the regulations are 7.46, 7.07, and 5.26, respectively. The maximum relative errors are 71.09%, 67.32%, and 75.90%, respectively. The minimum absolute errors are 0.21, 0.13, and 0.30, and the minimum relative errors are 1.79%, 2.03%, and 2.53%. According to the maximum and minimum absolute errors and relative errors, the prediction results of fitting formulas (1) and (2) of the new prediction model are better than those of the three empirical formulas in the regulations. Although the maximum relative error is relatively large, it can be seen that all relative errors of the new fitting formulas (1) and (2) are less than 26%, except for the predicted values of the 7607 narrow face in the Xingtai coal mine, the 4707 s-1 face in the Jingxing no. 1 coal mine,

Table 4: Error analysis of field measured values and fitting values of the working face floor failure depth in different mining areas.

Comparison types	Average value of in situ measurement (m)	Average value of fitting (m)	Error mean (m)	Error percentage (%)	Error variance	Mean square error
Fitting formula (1)	9.57	8.73	1.40	16.88	1.23	1.11
Fitting formula (2)	9.57	8.68	1.37	16.47	1.11	1.05
Statistical formula (3)	9.57	10.78	2.49	26.25	3.57	1.89
Statistical formula (4)	9.57	11.23	2.39	25.18	3.76	1.94
Statistical formula (5)	9.57	8.40	2.34	28.63	2.69	1.64

Table 5: Comparison between the values measured in situ and the fitted values of the floor failure depths.

Serial number	In situ value of floor failure depth (m)	Formula (1)		Formula (2)		Formula (3)		Formula (4)		Formula (5)	
		Absolute error (m)	Relative error (%)	Absolute error (m)	Relative error (%)	Absolute error (m)	Absolute error (m)	Relative error (%)	Absolute error (m)	Relative error (%)	Absolute error (m)
1	13.0	2.90	22.33	3.02	23.23	0.65	4.99	0.96	7.36	2.43	18.66
2	9.50	1.76	18.57	1.54	16.23	5.23	55.03	5.38	56.63	2.64	27.76
3	6.50	0.54	8.37	0.52	8.06	0.94	14.52	0.13	2.03	2.58	39.63
4	9.70	1.27	13.14	1.38	14.27	1.45	14.91	0.63	6.51	3.28	33.78
5	11.7	0.47	4.00	0.58	4.93	1.95	16.66	2.26	19.29	0.30	2.53
6	10.5	2.31	21.98	2.08	19.86	7.46	71.09	7.07	67.32	5.05	48.13
7	9.70	2.88	29.71	2.75	28.33	2.53	26.03	1.68	17.36	4.85	50.02
8	11.7	1.69	14.44	1.56	13.30	0.21	1.79	0.36	3.10	2.54	21.68
9	8.50	0.11	1.26	0.07	0.80	2.99	35.18	3.56	41.91	0.34	3.99
10	9.75	0.79	8.09	0.64	6.55	4.98	51.05	5.13	52.61	1.87	19.20
11	10.0	0.22	2.23	0.38	3.81	1.49	14.91	2.06	20.63	0.99	9.95
12	8.00	3.80	47.45	3.49	43.65	3.63	45.38	2.91	36.39	5.26	65.79
13	6.00	1.80	29.93	1.78	29.60	1.63	27.18	0.91	15.18	3.26	54.39
14	3.50	2.10	60.06	2.12	60.65	0.44	12.51	1.10	31.54	2.66	75.90
15	11.35	0.06	0.53	0.07	0.58	2.84	25.06	3.07	27.10	0.53	4.65
16	13.87	1.75	12.61	1.87	13.52	3.01	21.72	2.81	20.27	0.37	2.70
17	8.30	0.55	6.58	0.53	6.34	1.13	13.56	0.28	3.42	2.78	33.47
18	10.75	0.27	2.56	0.30	2.82	2.25	20.90	2.64	24.57	0.34	3.16

the 4707 s-2 face in the Jingxing no. 1 coal mine, and the 5701(1) face in the Jingxing no. 3 coal mine, which deviate greatly from the values measured in situ because of the small mining widths of their working faces. The results show that fitting formulas (1) and (2) of the new prediction model are closer to the values measured in situ and provide higher prediction accuracy and smaller errors than the empirical formulas in the regulations, thus meeting the needs of field engineering prediction.

In practical engineering applications, the accuracy of the two new floor failure depth prediction models is related to the selection of three parameters: mining width, mining depth, and mining height. The mining depth and mining height can be easily obtained by referring to the drilling column diagram and the actual layout of the working face. Through the analysis and verification of the values of the floor failure depth measured in situ in the eighteen above-mentioned mining areas, it can be seen that fitting formulas (1) and (2) have a certain feasibility in the prediction of the seam floor when special geological conditions, such as structure, are not encountered during the mining, and the prediction results are close to reality.

5. Conclusions

To address the difficulty of predicting the no. 5 coal seam floor failure depth in the Chenghe mining area under safe aquifer water pressure conditions, this paper studies the floor failure depth trends based on a comprehensive column diagram and both physical and mechanical properties and then draws the following conclusions:

(1) The FLAC3D finite difference program and numerical simulation method are used to simulate the failure range of the floor plastic zone in the coal seam during mining. The disturbance and failure characteristics of floor rock depth are analyzed in the no. 5 coal seam under two-factor (mining width and mining depth) and multifactor (mining width, mining depth, and mining height) conditions. This method can play an important role in the mine safety evaluation of the Chenghe mining area, which is threatened by high-pressure groundwater

(2) According to the simulation results under different conditions, the nonlinear regression fitting formula is obtained by using the nonlinear regression analysis method. It is also found that the effect of mining width on disturbance and floor failure depth is smaller than that of mining depth

(3) By comparing the values of the floor failure depth measured in situ with the fitting values, the fitting formula is proven to be feasible in practical applications

(4) Through the analysis and verification of eighteen examples of the floor failure depth of a mining face of a flat seam in China, the errors between the predicted values and the values of the floor failure depth measured in situ are compared and analyzed by three empirical formulas in the regulations and the nonlinear regression formulas obtained in this paper. The nonlinear fitting regression formula proposed in this paper is found to show better prediction ability than current methods, and the nonlinear fitting regression formula under the new prediction model has the best prediction accuracy, a relatively small error range, and a relatively high practical value in the prediction of floor failure depth, which can meet actual engineering needs

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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