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Research Article

Roof Water Damage Prediction and Evaluation of Sand-Mud Sedimentary Tectonic Strata

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The prediction and control of roof water disaster has been one of the key problems in the mining process of coal resources. With the increase of mining depth in the western mining area, the roof caving and communicating to the overlying water-bearing strata have led to an increasing number of roof water inrush accidents and deterioration of production environment of the working face. Aiming at the problem of roof water disaster prediction of sandy-argillaceous structural strata in Shanghaimiao mining area in China, firstly, the mechanical structure model of roof water inrush was built according to the parameters in the advance of the working face, and the thickness of the sandstone was used as the main controlling geological factor; the formula was derived for calculating the water-rich intensity F_{zh} of the overlying strata in the mining area. Secondly, starting from the height of the "Breakage-arch" development disturbance by combining the mechanical structure model of roof water inrush, the relative positional relation of the "Breakage-arch" and the water-bearing strata was analyzed, and a new method for judging the risk coefficient T_W of roof water inrush was proposed. Finally, according to the geological drilling histogram and the field conditions of #111084 working face of the no. 1 mine in Shanghaimiao mine area, the water-rich index and water inrush risk coefficient of overlying water-bearing strata were obtained by means of discriminant analysis, and the water inrush risk of #111084 working face was evaluated and predicted quantitatively. The water-rich property evaluation of water-bearing strata under the condition of low degree of hydrogeological exploration was evaluated accurately and reasonably, and a new evaluation method of the water disaster during mining was proposed.

1. Introduction

Chinese Jurassic recoverable coal resources account for more than 67% of the total coal reserves, which are mainly distributed in Western China. In the early stage, coal resource mining was mainly shallow mining [1, 2]. With the increase of coal mining depth, there are more and more accidents that roof caving communicates with the overlying aquifer, resulting in roof inrush disaster or deteriorating the production environment of the working face [3–5]. Facing the increasingly severe situation of roof water inrush disaster, many scholars have carried out a lot of research and made great progress in the prediction and treatment of roof water inrush disaster. Including Academician Wu's "three maps-two predictions method" for quantitative evaluation of roof water inrush conditions [6]. Li et al. and Zhang et al. [7, 8] established the mathematical model of indirect prediction of roof water disaster according to the multi-information composite analysis method of geographic information system (GIS). The concept of the water inrush possibility coefficient of the loose aquifer was proposed by Meng et al. and Gao [9, 10]. Fan et al. [11] comprehensively divided the risk of water inrush and sand break in the Yushenfu mining area and evaluated the risk of water inrush and sand break in the

mining area. Yi et al. [12] predicted the roof water inrush possibility area of the working face based on the discrimination results of the position of the main key strata of the overburden. Based on the influence of key strata position on the development height of the water diversion fracture zone, Xu et al. [13, 14] proposed a new method for predicting the height of the water diversion zone.

However, the conditions and mechanism of roof water inrush are complex. It is obviously not comprehensive to consider only whether the height of the water-conducting fracture zone induced by coal seam mining touches the roof aquifer. When the water-conducting fracture zone fails to reach the aquifer, the mining strata will break under the influence of secondary disturbance, and the disturbance range of the water-conducting fracture zone will change accordingly. Therefore, this paper considers the influencing factors of water-bearing sandstone thickness. According to the spatial relationship between overburden failure and overlying aquifer affected by mining, a discrimination method of roof water inrush possibility coefficient T_W is proposed, which is verified in a working face in Shanghaimiao mining area, China.

2. Spatial Structure Model of Roof Water Inrush

In the process of advancing the working face of coal mining, the fracture and fragmentation of the overlying strata are in continuous movement and development, and the relative positional relationship between the aquifer and the water-conducting fracture zone is regular; that is, it is determined by the strata movement. Therefore, the research on water inrush from coal seam roof should focus on the rock movement and focus on the damage range of overlying rock movement in the process of stope advancement and the spatial relationship between this range and the aquifer.

The rock stratum above the coal seam can be divided into two parts: overburden spatial structure and outer part of overburden spatial structure [15]. The outer part of the overburden spatial structure is the rock stratum without obvious movement outside the "Breakage-arch," which has little impact on the water permeability of the stope roof. With the advancement of the working face, the hanging space of the stope is increasing, the overlying strata are breaking, and the fracture positions are staggered from bottom to top, forming a "Breakage-arch" that has a direct impact on the water permeability of the stope roof (as shown in Figure 1). The moving rock structure in the "Breakage-arch" is called overburden spatial structure. In general, it can be considered that the development height of a "Breakage-arch" is the height of the water diversion fracture zone [16]. As for the relative position relationship between the "Breakage-arch" and the aquifer, the "Breakage-arch" communicates with an aquifer, and water inrush occurs immediately.

Some scholars believe that the key to the prevention of water inrush disaster is to clarify the location of water-bearing rock strata and the scope of the water-rich area [17, 18]. By adjusting the length of the working face and the position relationship of the open cut hole relative to the water-rich area, it is ensured that the fractured rock strata are interrupted during the advancement of the working face and do not spread to the water-bearing rock strata. Even if the fractured rock stratum does not affect the water-bearing rock stratum, there is a possibility of water inrush in the roof according to the separation catchment and hydrostatic water inrush [19].

3. Numerical Simulation of Development Law of "Breakage-Arch"

In the process of advancing the working face, the overburden is disturbed by mining, and the "Breakage-arch" continues to develop and expand upward, resulting in a large number of network fractures, which is very easy to induce water inrush in the stope. In order to study the relationship between the length of the working face and the development height of "Breakage-arch," combined with the field peeping borehole observation results and exploration borehole data in Shanghaimiao mining area, a FLAC^{3D} numerical simulation model was established (as shown in Figure 2). Model size is long × wide × height = 500 m × 300 m × 300 m, the model contains 121875 grid elements and 146256 nodes, and the excavation dimensions of the simulated working face are 150 m, 180 m, 210 m, and 240 m, respectively. The M-C constitutive model is used to describe the mechanical response of overburden under tension failure and instability. The vertical stress and horizontal stress applied in the model are $\sigma_{zz} = 20$ MPa, $\sigma_{yy} = 16$ MPa, and $\sigma_{xx} = 16$ MPa. The mechanical parameters of coal and various rocks are shown in Table 1. After the model calculation reaches the initial equilibrium, the working face is excavated according to the dimensions of 150 m, 180 m, 210 m, and 240 m and calculated to the default equilibrium state of the software to obtain the development characteristics of the plastic zone as shown in Figure 3.

The numerical simulation results show that the development height of the plastic zone increases with the increase of the width of the working face. After measurement and comparison, the development height of the plastic zone is about 1/2 of the width of the working face.

4. Discriminant Analysis of Roof Water Inrush Possibility

The water yield of the aquifer is measured by the specific yield. The greater the specific yield, the stronger the water yield of the aquifer and vice versa. Therefore, the specific yield can directly reflect the water abundance of the aquifer. According to the engineering practice, the degree of hydrogeological exploration in most coal mining areas in China is low, the number of pumping (drainage) test is limited, the data of unit water inflow can be obtained is less, the water abundance of the aquifer cannot be fully reflected, and the high-precision evaluation and prediction of water abundance of the aquifer cannot be realized. Therefore, based on previous studies, the author puts forward a new method to distinguish the risk of roof water inrush.

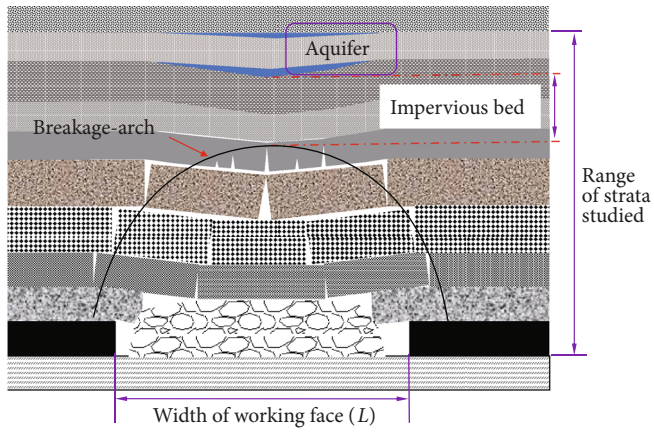

Figure 1: Spatial structure model of water inrush.

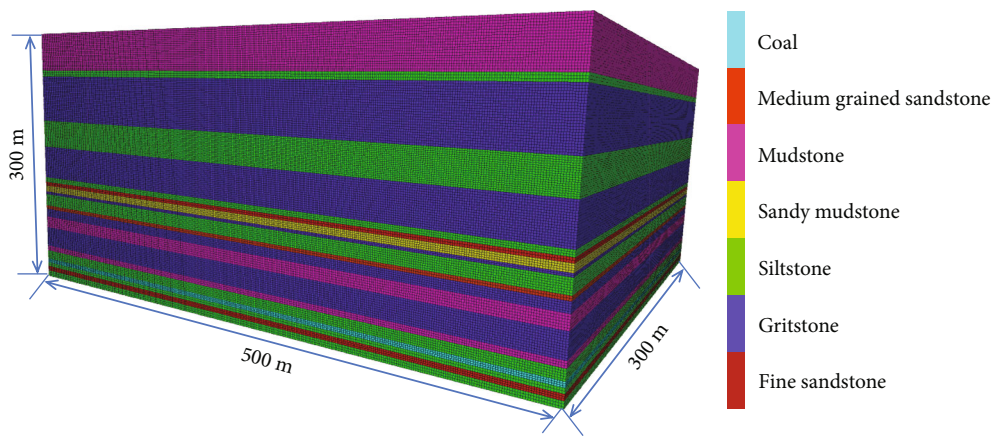

Figure 2: Numerical simulation model.

Table 1: Properties of coal and rock mass used in the numerical model.

Rock character	Poisson's ratio	Density (kg·m^{-3})	Cohesion (MPa)	Internal friction angle (°)	Bulk modulus (GPa)	Shear modulus (MPa)	Tensile strength (MPa)
Mudstone	0.25	2470	1.78	25	2.41	4.13	0.70
Siltstone	0.22	2602	3.10	33	7.21	2.80	0.80
Gritstone	0.32	2700	6.20	34	4.80	2.20	3.00
Fine sandstone	0.20	2590	3.96	50	6.98	2.80	1.35
Sandy mudstone	0.27	2490	1.79	26	2.44	4.23	0.75
Coal	0.31	1347	1.21	30	2.13	1.35	0.12

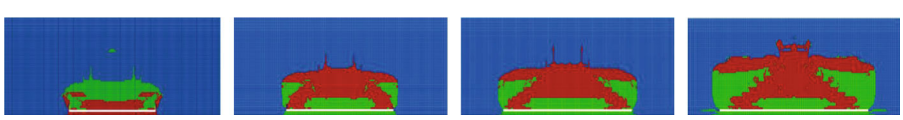

Figure 3: Development law of plastic zone under different working face width.

4.1. Water Rich Index. The lithology of sandy-argillaceous sedimentary structures can be divided into two categories: (1) conglomerate rocks, coarse sandstone, and fine sandstone are called sandy rocks (or brittle rocks) because of their coarse particles and high brittleness; (2) siltstone, mudstone, sandy mudstone, and carbonaceous mudstone are

called argillaceous rocks (or plastic rocks) because of their fine particles and strong plasticity. Sandy rocks have large primary porosity and are prone to produce a large number of fractures, which are the main water storage space. Because there are certain differences in mechanical properties among strata in the stratum, the conditions for forming the separation layer are met. During the formation of the separation layer, the fissure water in the sandstone strata will continue to collect into the separation layer. With the increase of collected water, the separated strata water will exert pore water pressure and load on its lower rock stratum. This leads to the fracture and instability of the lower rock stratum and the formation of water inrush in the working face. However, there are argillaceous strata with fine particles and strong plasticity in sandy-argillaceous sedimentary structural strata. It can withstand a certain tension failure, is not easy to produce cracks, can curb the expansion of water storage space, and hinders the collection of pore fissure water to the separation strata. Therefore, taking the adjacent argillaceous rock overlying the key strata as the top boundary and the interval between the top boundary and the roof of the working face as the effective research interval, the proportion of the cumulative thickness of brittle rock within the effective research interval can reflect the water yield in the overlying strata.

$$F_Z = \frac{\sum D_i}{H_y} \times 100\%, \tag{1}$$

where F_Z is the water abundance index (dimensionless) $\sum D_i$ is the cumulative thickness of sandy rock strata within the effective study interval (m), and H_y is the vertical distance between the adjacent argillaceous rock above the key strata and the roof of the working face (m).

4.2. Water Inrush Possibility Coefficient. The risk of water inrush from the roof is determined by the height of the "Breakage-arch" and the water content of the roof. The larger the scope of disturbing and damaging the aquifer and the stronger the water abundance, the risk of water inrush is relatively high. In order to quantitatively evaluate the possibility of water inrush into the stope of indirectly water-filled aquifer, the water inrush possibility coefficient is introduced here. The probability of water inrush in stope is evaluated by measuring the safe distance between the water-conducting fracture and the upper aquifer. Without considering other factors, the calculation formula is [20]

$$T_{\mathrm{wy}} = \frac{H_{\mathrm{gs}} - H_{\mathrm{fs}}}{H_{\mathrm{fs}}}, \tag{2}$$

where T_{wy} is the water inrush possibility coefficient of predecessors (dimensionless), H_{gs} is the thickness of the water-resisting strata, i.e., the distance between the coal seam roof and the upper aquifer (m), and H_{fs} is the theoretical calculation value of water-resisting coal (rock) pillar (m).

There are differences in physical and mechanical properties in the strata of sandy-argillaceous sedimentary structures, which determine that the subsidence process of overburden must be uncoordinated movement. Therefore, the separation space was generated, which provided physical space development conditions for water inrush dangerous water bodies, and the main separation strata were developed below the key strata. During the advancement of the working face, the overburden on the main roof was broken, rotated, and sunk. The main roof continuously evolves dynamically in space, forming a "Breakage-arch" structure in a two-dimensional plane, resulting in a large number of water diversion fractures. This increases the possibility of connecting the aquifer with the water-conducting fracture zone.

Regardless of the hulking sex of the overburden above the main roof, the fracture and bending of the overburden from the main roof to the key strata have similar morphology. In the calculation of deformation, it can be regarded as a multi-strata ring with the same center, as shown in Figure 4.

According to the geometric relationship in Figure 4,

$$|OA_1| = H_C + H_{zj}\text{-}\mathrm{K_C}H_{zj}, \tag{3}$$

$$|A_1A_n| = \cos^{-1}\theta \sum_{i=1}^{n} D_i, \tag{4}$$

$$H_l = |OA_1| + |A_1A_n|, \tag{5}$$

where A_i (i ranges from 1 to n) is the maximum settlement point of the overburden except the direct roof, D_i is the thickness of overburden of strata i (m), θ is the turning angle of overburden (°), H_C is the height of coal mining (m), H_{zj} is the thickness of the direct roof (m), K_C is the residual crushing expansion (dimensionless), and H_l is the development height of the lowest point of separation strata (m).

With the development of the separation space, the pore water and fissure water of adjacent sandy strata are continuously collected in the separation layer (as shown in Figure 5). The collected water exerts an additional load on the lower unbroken barrier strata. When the applied load exceeds the tensile strength of the impervious bed (σ_t), it is very easy to induce the instability of barrier strata and finally leads to water inrush in the working face. Therefore, according to the spatial relationship between the water of the abscission layer and the "Breakage-arch," the ratio of the development height of the "Breakage-arch" to the lowest point height of the catchment separation strata is taken as the discrimination basis. At the same time, the discrimination formula of water inrush possibility is obtained by combining the position of key strata and the tensile strength of the impervious bed:

(1) Judging from the geometric relationship:

$$T_{W1} = \frac{H}{H_l} \times 100\%, \tag{6}$$

$$H = kL. \tag{7}$$

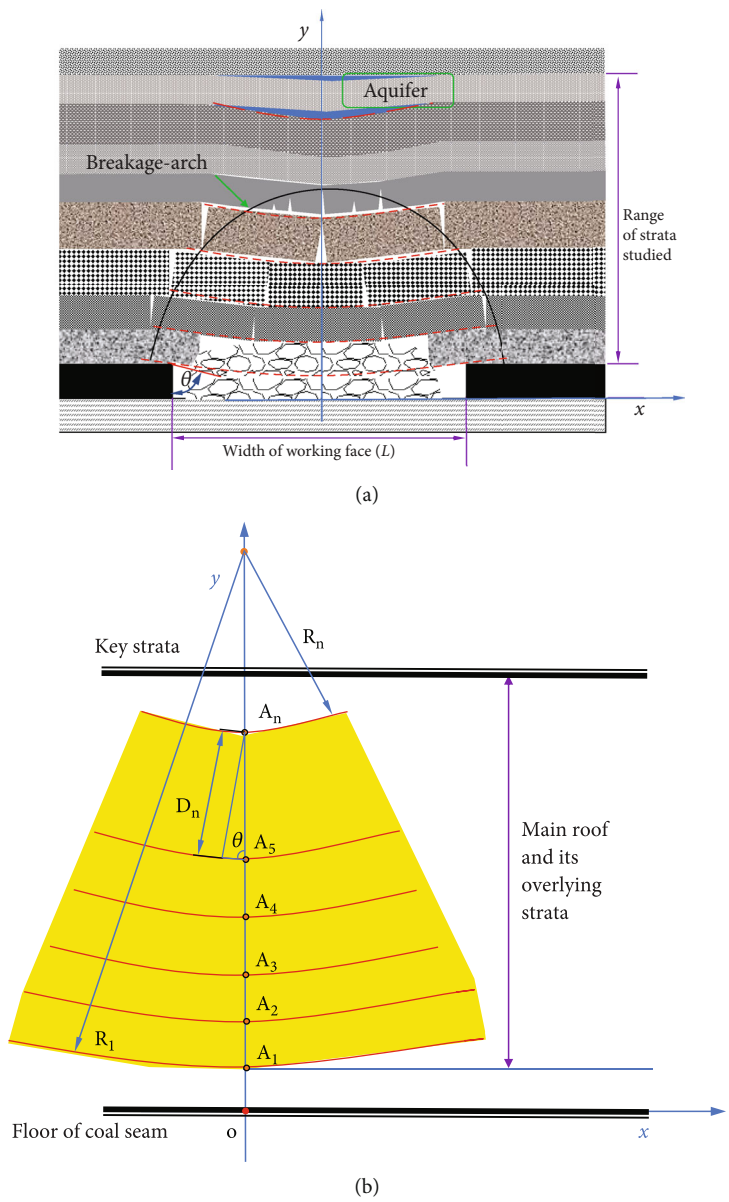

Figure 4: Schematic diagram of final position state of upper strata fracture and subsidence.

(2) Judging from the stress state:

$$T_{W2} = \frac{\rho g\left(H_g - H_l\right)}{\sigma_t} \times 100\%, \tag{8}$$

where T_W is the water inrush possibility coefficient (dimensionless), H_l is the height of the lowest point of separation (m), H is the development height of "Breakage-arch" (m), H_g is the height of key strata (m), L is the width of the working face (m), k is the proportionality coefficient, $k = 0.5 \sim 0.7$ (dimensionless), σ_t is the tensile strength of the rock as the impervious bed (Pa), ρ is the density of water in the separation strata (kg/m^3), and g is the gravitational acceleration (about 9.8 m/s^2).

The greater the value of T_W, the greater the risk of water inrush in the working face. When T_W approaches 100%, it indicates that the spatial position of the "Breakage-arch" and the aquifer is infinitely close (as shown in Figure 6). The impervious bed was infinitely close to the breaking instability state, which was very easy to induce water inrush in the working face.

5. Engineering Verification

5.1. Geological Conditions of the Project. Shanghaimiao no. 1 coal mine is located in etokeqian banner, Inner Mongolia. The total amount of coal resources is about 14.3 billion tons. The mining area is a typical geological structure of sandy argillaceous sedimentary formation, and the geological profile is shown in Figure 7. The Jurassic Yan'an Formation

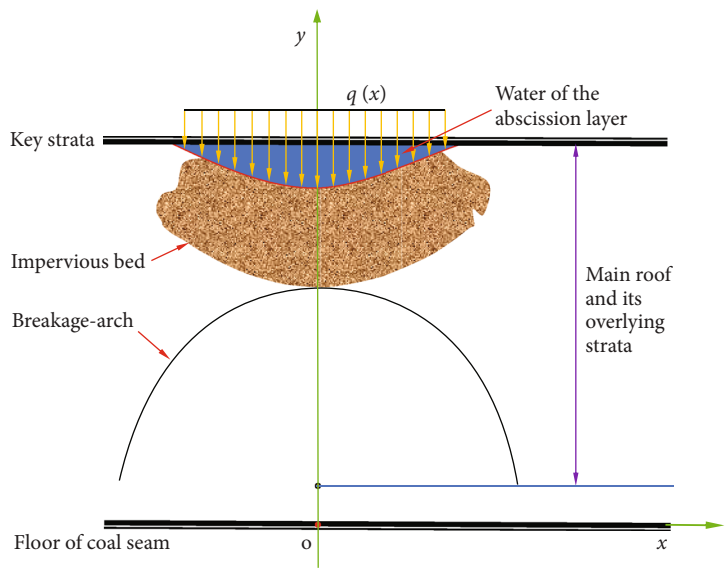

Figure 5: Mechanical model of roof structure when water inrush was about to occur.

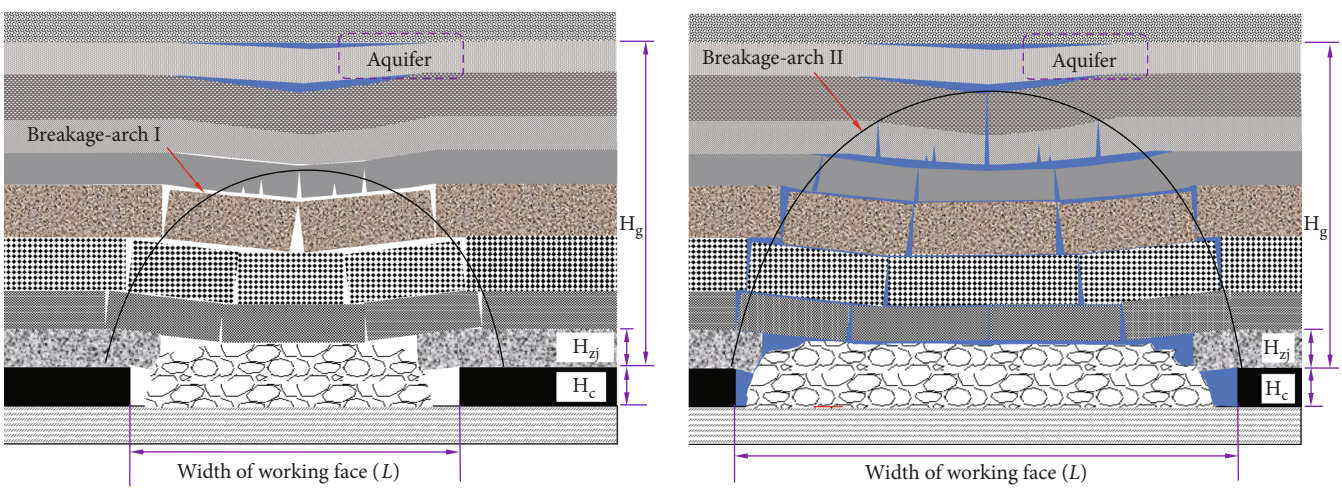

Figure 6: The relationship between the development height of "Breakage-arch" and water-bearing strata.

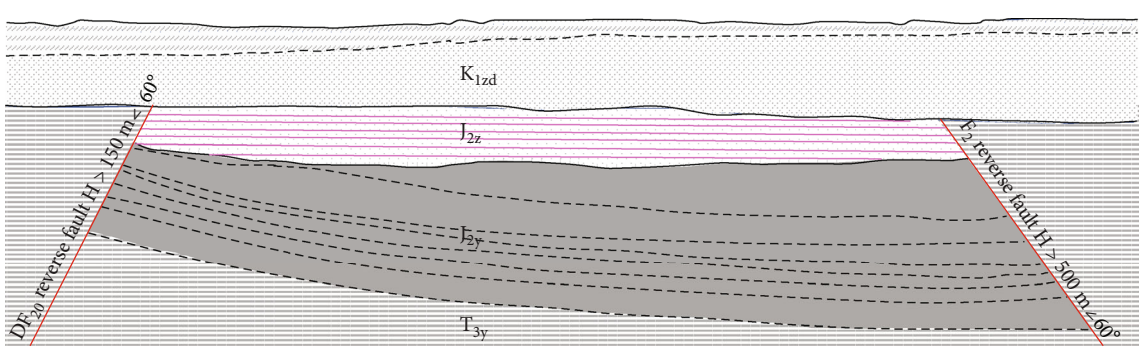

Figure 7: Geological profile of minefield.

(J_{2y}) is a coal-bearing formation, which is overlaid by Jurassic Zhiluo Formation (J_{2z}), Cretaceous Zhidan group (K_{1zd}), and underlying by Triassic Yanchang Formation (T_{3y}).

5.2. Aquifer and Water Yield. The main aquifers of Shanghaimiao no. 1 coal mine are the Cretaceous conglomerate aquifer, Jurassic Yan'an Formation sandstone aquifer, and Jurassic Zhiluo Formation sandstone aquifer.

(1) The average thickness of the aquifer section of Jurassic Zhiluo Formation sandstone was 41.0 m, the elevation of water level was +1220~+1252 m, the

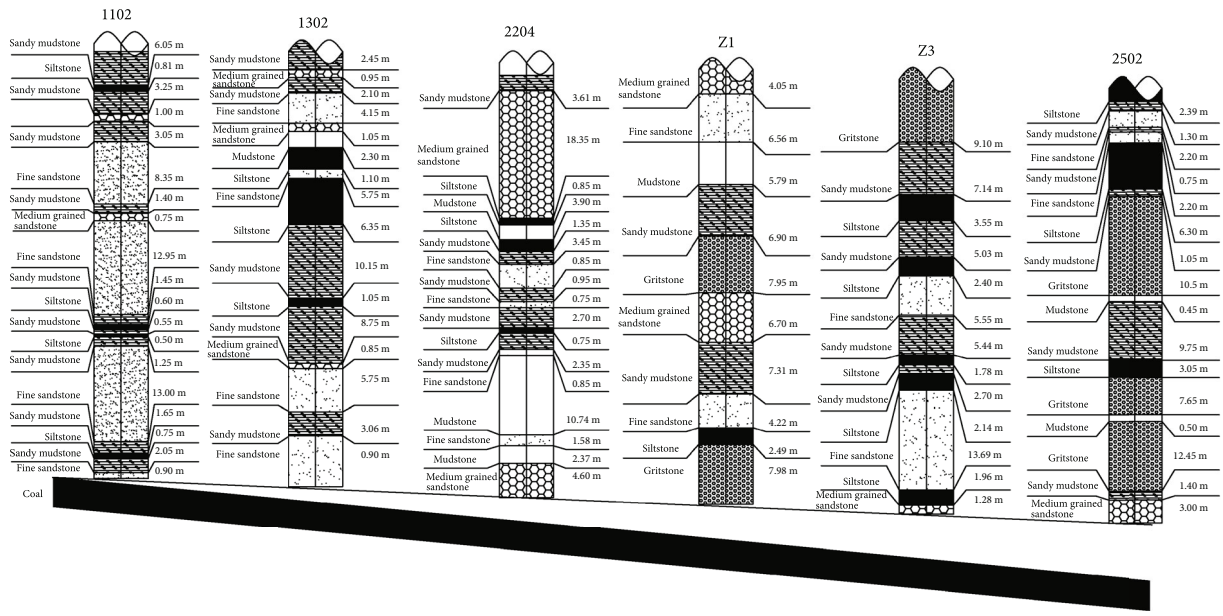

Figure 8: Part of borehole column of "Qilizhen sandstone" in Zhiluo Formation.

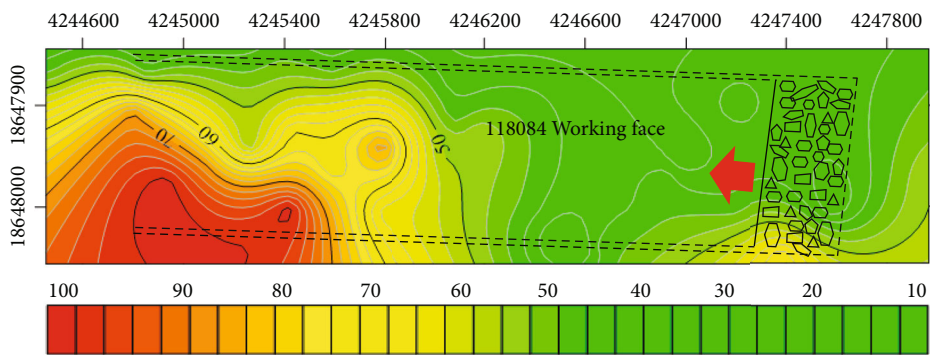

Figure 9: Contour map of the water-rich index of #111084 working face.

permeability coefficient was 0.05~0.35 m/d, and the specific yield was 0.017~0.015 L/(s·m)

(2) The average thickness of the Cretaceous conglomerate aquifer was 64.5 m, the elevation of water level was +1240~+1269 m, the permeability coefficient was 0.049~0.341 m/d, and the specific yield was 0.047~0.341 L/(s·m)

(3) The aquifer group of Jurassic Yan'an Formation sandstone is pore (fissure) water, the permeability coefficient was 0.0029~0.1970 m/d, and the specific yield was 0.0027~0.0281 L/(s·m)

The maximum mining height of coal seam #8 is 3.8 m, the length of the working face is 220 m, and the maximum thickness of the waterproof safety coal (rock) pillar is 20 m. According to the drilling data (Figure 8 shows some drilling data) and the calculation formula of water yield index (1), the contour map of the water-rich index of #111084 working face is obtained (as shown in Figure 9).

5.3. Water Inrush Possibility of Roof in Working Face. Taking the geological conditions of #111084 working face as an example, the water level change of #z1 hydrological observation wells near the water inrush position of the working face is measured, as shown in Figure 10.

(1) During the water storage in the separation space: the water level of Zhiluo Formation decreased by 13.59 m after being advanced by 0~110 m (data from July 13 to July 31)

(2) During the formation of the bend zone: the advance was 110~140 m, the overburden subsidence occurred, and the water level rose by 0.972 m (data from July 31 to August 5)

(3) Water inrush: when advancing to 141 m, the water diversion fissure destroys the separation closed space above the working face and water inrush occurs. The maximum water volume is 2000 m^3/h, and the water level drops by 29.12 m

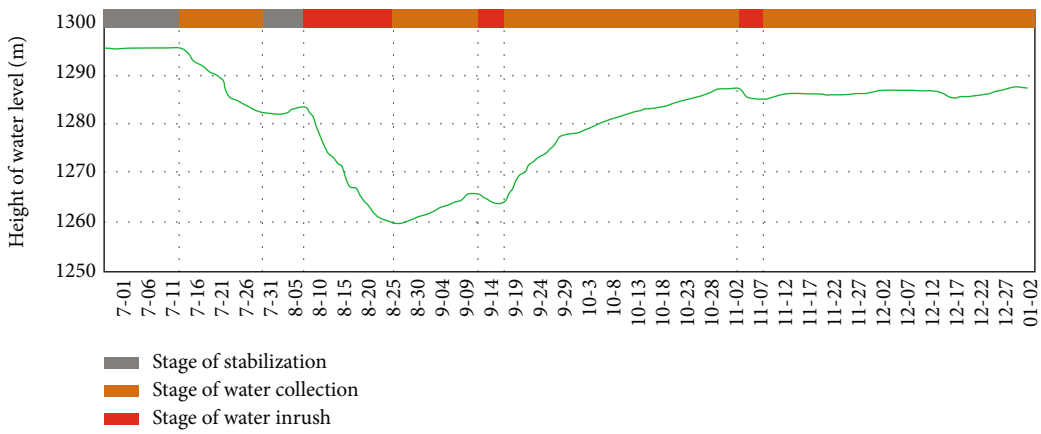

Figure 10: Water level change map of Z1 hydrological observation hole in #111084 working face.

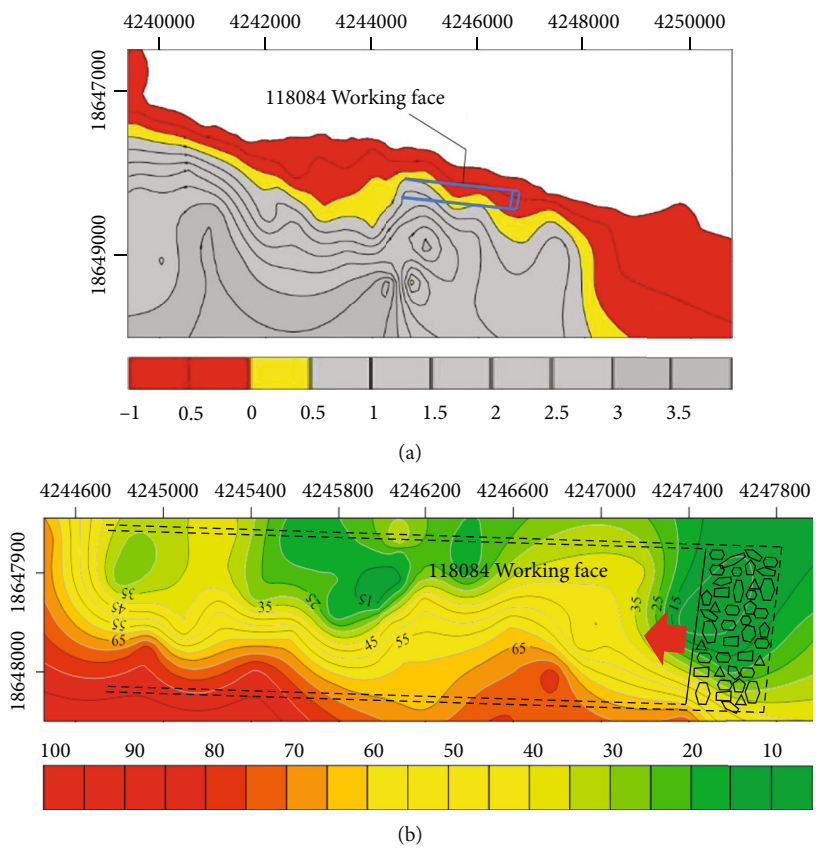

Figure 11: Contour map of water inrush possibility of #111084 working face.

According to the observed data on site, #111084 working face has the conditions for water inrush, and it is necessary to predict the possibility of water inrush in the unmined area.

The position of the key strata and the thickness of the immediate roof were determined according to the geological borehole histogram. Combined with the water-rich index and using the discriminant Equations (6) and (8) of the water inrush possibility coefficient, the water inrush possibility of the overlying aquifer during mining in the 111084 working face of no. 1 mine in Shanghaimiao mining area was evaluated. Due to the difference of lithology of immediate roof, the value range of crushing expansion coefficient fluctuates between 1.15 and 1.4 [21]. The calculated water inrush possibility coefficient and coordinates were imported into surfer 12.0 to obtain the contour map (as shown in Figure 11) of water inrush possibility coefficient. The contour map was filled with gradient colors based on numerical intervals. Among them, the red-filled part indicates that there was a great possibility of "Breakage-arch" contacted

the aquifer in this area. The green-filled area indicates that the possibility of a "Breakage-arch" contacting the aquifer was very small. Referring to the "three-line" method of ponding in goaf, the area ($35 < T_W \leq 65$) was filled with yellow, which belongs to the warning range.

Compared with the existing results [20], this paper mainly modifies the discrimination method of the water-rich index and the possibility of water inrush in the working face. When the mining parameters of coal seam were included, the predicted coefficients were positive, the fluctuation range of coefficients was 10~80+, the accuracy of prediction results is high, and the variable range of coefficients is large. When having the same geographical coordinates, Figure 11(a) is the contour map of prediction results drawn by using the water inrush possibility index method before correction, and Figure 11(b) is the contour map of prediction results drawn by using discriminant Equation (2) and Equation (3) in this paper. The comparison shows that the modified discrimination method proposed in this paper has good prediction accuracy and improves the practicability of water inrush possibility prediction zoning.

6. Conclusion

(1) The water abundance in sandy argillaceous sedimentary structural strata is uneven. The proportion of the thickness of sandy strata in the whole overburden is taken as the main index to evaluate the water abundance. Combined with the parameters of the working face and the overburden structure model of water inrush, the evaluation method of water yield was established

(2) In view of the evaluation and prediction of water damage to the roof of the working face under the condition of sandy argillaceous sedimentary structural stratum, the damage range of the "Breakage-arch" to the aquifer and the water yield strength of the aquifer are comprehensively considered. Combined with the parameters of the working face and the residual dilatancy coefficient of the direct roof, the discrimination formula of the possibility coefficient of water inrush was proposed

(3) According to the new discrimination formula proposed in this paper, the water-rich index of overburden and the possibility coefficient of water inrush are obtained, and the possibility of water inrush in #111084 working face was quantitatively evaluated and predicted. It realized the scientific evaluation of water abundance and water inrush possibility of sandy argillaceous sedimentary structural strata under the condition of low degree of hydrogeological exploration

Data Availability

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

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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References

[1] S. Chen, Y. Wang, W. Yuezhong, Z. Wang, and W. J. Zhang, "Coal resources and development potential in Northwest China," *Northwestern Geology*, vol. 39, no. 4, pp. 40–56, 2006.

[2] H. Li and X. Tian, "Comprehensive evaluation and analysis of exploitation potential of coal resource in northwest of China," *Coal Geology & Exploration*, vol. 26, no. S1, pp. 1–4, 1998.

[3] E. Brunetti, J. P. Jones, M. Petitta, and D. L. Rudolph, "Assessing the impact of large-scale dewatering on fault-controlled aquifer systems: a case study in the Acque Albule basin (Tivoli, central Italy)," *Hydrogeology Journal*, vol. 21, no. 2, pp. 401–423, 2013.

[4] S. Kerang, "Numerical study identifying the factors causing the significant underestimation of the specific discharge estimated using the modified integral pumping test method in a laboratory experiment," *Journal of Contaminant Hydrology*, vol. 180, no. 9, pp. 1–11, 2015.

[5] A. T. Tizro, K. Voudouris, and Y. Basami, "Estimation of porosity and specific yield by application of geoelectrical method-a case study in western Iran," *Journal of Hydrology*, vol. 454-455, pp. 160–172, 2012.

[6] W. Qiang, "Dynamic visualization and prediction for water bursting on coal roof based on "three maps method"," *Journal of China Coal Society*, vol. 41, no. 12, pp. 2968–2974, 2016.

[7] K. Li, Y. Zeng, and Y. Shang, "The application of "three maps-two predictions" method based on GIS," *Coal Geology & Exploration*, vol. 43, no. 2, pp. 58–62, 2015.

[8] H. Zhang, R. Zhou, D. Guo, and P. Du, "Investigation on predicting roof water gush in coal mines based on multi-factor analysis," *Journal of China University of Mining& Technology*, vol. 34, no. 1, pp. 115–119, 2005.

[9] Z. Meng, Y. Gao, L. Aihong, R. Wa, X. Qi, and C.-Y. Hu, "Water inrush risk evaluation of coal mining under quaternary alluvial water and reasonable design method of waterproof coal pillar," *Journal of Mining and Safety Engineering*, vol. 30, no. 1, pp. 23–29, 2013.

[10] Y. Gao, "Four-zone model of rock mass movement and back analysis of dynamic displacement," *Journal of China Coal Society*, vol. 21, no. 1, pp. 51–56, 1996.

[11] L. Fan, X. Ma, H. Jiang, and S. Cheng, "Risk evaluation on water and sand inrush in ecologically fragile coal mine," *Journal of China Coal Society*, vol. 41, no. 3, pp. 531–536, 2016.

[12] M. Yi, W. Zhu, L. Li, Z. Xu, and X. Jia-lin, "Water inrush mechanism and prevention for fourth panel roof in Bulianta coalmine," *Journal of China Coal Society*, vol. 33, no. 3, pp. 241–245, 2008.

[13] X. Jialin, W. Zhu, and X. Wang, "New method to predict the height of fractured water-conducting zone by location of key strata," *Journal of China Coal Society*, vol. 37, no. 5, pp. 762–769, 2012.

[14] X. Jialin, M. Qian, and H. Jin, "Study and application of bed separation distribution and development in the process of strata movement," *Chinese Journal of Geotechnical Engineering*, vol. 24, no. 5, pp. 632–636, 2004.

[15] Z. Wen, *Study on Key Technologies and Mechanical Model of Gob-Side Retaining Entry*, Shandong University of science and technology, 2011.

[16] Z. Wen, S. Jing, Z. Song et al., "Study on coal face spatial structure model and control related dynamic disasters," *Coal Science and Technology*, vol. 47, no. 1, pp. 52–61, 2019.

[17] A. F. Diogo and M. C. Oliveira, "A simplified approach for the computation of steady two-phase flow in inverted siphons," *Journal of Environmental Management*, vol. 166, pp. 294–308, 2016.

[18] A. M. Sape, "A head loss model for slurry transport in the heterogeneous regime," *Ocean Engineering*, vol. 106, pp. 360–370, 2015.

[19] W. Qiao, W. Li, and X. Li, "Mechanism of "hydrostatic water inrush" and counter measures for water inrush in roof bed separation of a mining face," *Journal of Mining & Safety Engineering*, vol. 28, no. 1, pp. 96–104, 2011.

[20] Y. Lv, H. Li, and Y. Xia, "Prediction and evaluation study on coal seam roof water inrush based multi-type four-double method," *Coal Science and Technology*, vol. 47, no. 9, pp. 219–228, 2019.

[21] X. Chen, S. Chengdong, X. Tang, and W. Guo, "Experimental study of effect of water-saturated state on compaction property of crushed stone from coal seam roof," *Chinese Journal of Rock Mechanics and Engineering*, vol. 33, no. S1, pp. 3318–3326, 2014.