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Research article

Study of roof water inrush forecasting based on EM-FAHP two-factor model

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Abstract: To solve the problem of predicting and evaluating coal mine roof water inrush accidents, based on the background of Hongliu coal mine， the relevant weight values of the main control factors of water inrush were determined based on the water-richness index method, combined with the entropy method and FAHP two-factor method. The grid processing function of GIS and the kriging interpolation method are used to draw thematic maps of the main controlling factors, and the weight values of the water permeability indicators are coupled into the GIS. The FLAC^{3D} numerical simulation software is used to analyze the water-conducting fracture zone after the mining of the Hongliu Coal Seam numerical simulation of development and water pressure distribution changes. The results show that the permeability hazard zoning map obtained by the EM-FAHP two-factor model is in line with the results of the damage height and the increased water pressure zone obtained by the numerical simulation.

Keywords: entropy method; fuzzy analytic hierarchy process; water-richness index method; roof water inrush; numerical simulation

1. Introduction

In China's energy consumption structure, coal accounts for more than 50%. China is an oil-poor, less natural gas, coal-rich country, which determines the solid position of coal in conventional energy. In the process of coal mine construction, production and mining, water inrush in mines occurs frequently, causing a large number of casualties and loss of plant and equipment, which seriously restricts the safe production of mines. Especially in recent years, there have been frequent incidents of roof penetration in deep stopes, causing significant loss of personnel and property. Therefore, it is of practical significance to predict and evaluate the prevention and control of coal seam roof water penetration, promote the sustainable development of coal mining industry and guarantee production safety.

On the basis of a large number of theories and field studies, many scientists have made contributions to the quantitative evaluation of roof water inrush and promoted the development of coal seam roof water inrush evaluation and analysis. Scholars, represented by Liu [1], proposed the theory of the “upper three zones” and the empirical formulas for calculating the development of water-conducting fractures under different roof types conditions; Gao [2] from Shandong University of Science and Technology put forward the theory of "four zones" of rock movement based on this theory, dividing the overlying rock into four zones from top to bottom: loose sedimentation zone, bending zone, separation zone and fracture zone ; Professor Qian [3], an academician of the Chinese Academy of Engineering, proposed the key layer theory after an in-depth study of mine pressure and rock layer control, which further broadened the understanding of the permeability mechanism. Wang et al. [4] conducted numerical simulation by UDEC fluid-solid coupling to study the damage mechanism of coal mining on overburden aquifers [5]; Wu's [6,7] academician team conducted research on the upper three zones and proposed the "three maps-two predictions" method, using the principle of multi-source geological information compound superposition to make the prediction model more scientific. V. M. Shik [8] analyzes the influence of different coal mining methods on pressure control of coal mining, which has a stimulating effect on the development of water-conducting fractures in the roof. Qi [9] established a mathematical model for the dynamic changes of groundwater level and inrush flow to study the development of channels near water-conducting faults and the process of seepage-inrush, revealing the mechanism of fault activation and water inrush.

In the quantitative calculation link of the water-richness index, AHP is based on the traditional Delphi method, which further mathematically processes the knowledge, experience, and value judgments of relevant experts and technicians, simplifies the complex problem into an orderly recursive hierarchy, and quantifies the important comparative degree of related factors as the magnitude of the weight value [10]. However, AHP did not consider the ambiguity of human judgment when constructing the judgment matrix, and there is a difference between the consistency of the judgment matrix and the consistency of decision-making thinking [11]. Therefore, by combining fuzzy mathematics, FAHP, which overcomes the limitations of traditional AHP and the subjectivity of human thinking, is used to achieve ranking of the importance of the main control factors [12,13]. The entropy method (EM) is a weight judgment based on the information characteristics of the sample data itself, which can be an effective supplement to the objective blind spot of objectivity of FAHP [14,15]. In this paper, we choose a two-factor weight determination method based on EM-FAHP, and use the data processing and spatial analysis functions of GIS to establish a multi-factor geological compound model, draw a water-rich zoning map, and realize the quantitative data perspective expression of qualitative factors, and calculates the development height of the water-conducting fracture zone in the mining area, coupled to obtain the final water-inrush risk zone.

2. Summary of the study area

Ningxia Hongliu Coal Mine is located in the southern part of the Yuanyang Lake mining area in the Ningdong Coal Base, at the western edge of the Mu Us Desert. It has a semi-arid desert continental monsoon climate with large temperature differences between day and night and little precipitation, mostly in summer and autumn. The surface of the mining area is dominated by Quaternary aeolian sand, with a small amount of bedrock exposed in the southwest. The fractured pore aquifer of the Middle Jurassic Zhiluo Formation is the main permeable water source for the roof water inrush disaster of Hongliu Coal Mine. The nature of the sandstone at the bottom of the aquifer is relatively stable, mainly coarse-grained sandstone, mostly the roof of the working face, which is a water-filled aquifer on the roof of the coal seam.

3. Establishment of two-factor analysis model for water richness

3.1. Establish a water-richness evaluation index system

Coal roof water inrush is a comprehensive hydrogeological phenomenon that is affected by various factors such as roof aquifer thickness, permeability coefficient, geological structure, thickness ratio of friable rocks to plastic rocks, etc. for different mines or even different working faces of the same mine. The mining environment is not the same, and the main control factors selected are also quite different. The selected main control factors directly determine the establishment of the evaluation area and the accuracy of the prediction results. According to the hydrogeological data of Hongliu coal mine and combined with the available report data, the factors affecting water production were analyzed and screened. Aquifer thickness, aquiclude thickness, thickness ratio of friable rocks to plastic rocks, core recovery percentage and permeability coefficient are the main influencing factors.

3.1.1 Influencing indicators for the evaluation of the danger of permeable coal roof

The thickness of the aquifer reflects the water content of the aquifer. The water content of the aquifer is positively related to its thickness. The greater the thickness of the aquifer, the better the water content and the greater the risk of water inrush.

The thickness of the aquiclude refers to the rock layer with extremely low water permeability. The water richness of the aquifer is negatively related to it. The thicker the aquiclude, the worse the water richness.

The thickness ratio of friable rocks to plastic rocks refers to the proportional relationship between them. Siltstone, shale, mudstone, and sandy mudstone in the rock formation are plastic rocks. When they are damaged by stress, they undergo plastic deformation to release the stress, and the water permeability remains unchanged. However, medium sandstone, fine sandstone, medium-fine sandstone and limestone are friable rocks. When rock is damaged under stress, its failure modes are shear failure and tensile failure. Therefore, the internal joints and fissures of brittle rocks develop and the permeability increases. The thickness ratio of brittle-plastic rock in the rock layer reflects the permeability of the rock layer. The larger the proportion of brittle rock, the better the water permeability.

The core recovery percentage refers to the ratio of the core length of the aquifer to the thickness of the aquifer. It reflects the index of the intersection of rock integrity and rock fractures. The lower the core sampling rate, the more rock fractures, the higher the degree of fracture development, and the greater the hydraulic conductivity. Permeability coefficient is an important index used to evaluate the water richness of aquifers. It indicates how easy it is for the fluid to pass through the void medium and is related to the rock properties and the physical properties of the fluid. The greater the permeability coefficient, the stronger the permeability capacity.

3.1.2 The establishment of main control factors and weight

(a) Entropy Method (EM):

The entropy method (EM) determines the target weight by judging the dispersion of the data set [16]. The smaller the degree of discrete variation of data, the smaller the entropy value, the more effective the information; conversely, the greater the entropy, the less effective information. Using the entropy of different index data to determine the weight of the main control factor completely depends on the actual data, which is more realistic and objective. The steps are as follows [17]:

(a1) Data standardization processing. Since the unit magnitude and attribute of the initial value of each indicator in the evaluation system are different, in order to eliminate the influence of the above factors on the evaluation results, the normalization method is used to standardize the initial value of each indicator, that is, the absolute value of the original data of each indicator is converted into relative values values through standardization, making different indicators more comparable. Usually, different formulas are selected for standardization according to different indicator types.

Positive indicators:

$$Y_{ij} = \frac{X_{ij} - \min X_{ij}}{\max X_{ij} - \min X_{ij}} \tag{1}$$

Negative indicators:

$$Y_{ij} = \frac{\max X_{ij} - X_{ij}}{\max X_{ij} - \min X_{ij}} \tag{2}$$

(a2) Determine the standard matrix $Y=\{Y_{ij}\}m\times n$ of the original data, and calculate the proportion of the data value of the *i*-th main controlling factor at the *j*-th drilling point.

$$P_{ij} = \frac{H_{ij}}{\sum_{i=1}^{n} H_{ij}} \tag{3}$$

(a3) Calculate the information entropy E_j of the *j*th index according to the entropy calculation formula

$$E_j = -k\sum_{i=1}^{n} P_{ij} \ln P_{ij} \tag{4}$$

Among them, $k > 0$,*ln* is the natural logarithm, and the constant k is related to the number of samples n. Generally, if $k=1/\ln n$, then $0 \le E_j \le 1$.

(a4) Calculate the difference coefficient D_j of the *j*th index according to the information entropy. The difference coefficient of the index directly affects the size of the weight. The difference coefficient can be calculated directly by subtracting the information entropy E_j of the index from 1. The specific calculation formula of the difference coefficient D_j of the *j*th index is:

$$D_j = 1 - E_j \tag{5}$$

(a5) Use the difference coefficient to calculate the weight W_j of the jth index. Using the entropy method to calculate the weight of each indicator, the essence of which is to use the difference coefficient of the indicator information to calculate the weight. The greater the difference coefficient, the greater the weight. The weight calculation formula of the jth index is

$$W_j = \frac{D_j}{\sum_{i=1}^{n} D_J} \tag{6}$$

Write FUNCTION HANDLE based on the principle of entropy method based on MATLAB language. According to the drilling data in the hydrogeological data, the main control factors can be calculated by calling the script program as shown in Table 1.

Table 1. Determine the weight of main control factors by entropy method.

Aquifer thickness	Aquiclude thickness	Thickness ratio of friable rocks to plastic rocks	Core recovery percentage	Permeability coefficient
0.1765	0.1139	0.0901	0.2872	0.3323

(b) FAHP:

The Analytic Hierarchy Process (AHP) is a practical decision-making method proposed by the American operations researcher Professor T. L. Saaty in the mid to late twentieth century [18]. This method can qualitatively and quantitatively analyze multiple plans or targets. Such as multi-objective, multi-criteria, and multi-factor decision-making scheme selection problems that do not have a complete structural hierarchy. In view of these problems, the analytic hierarchy process can better divide the hierarchical structure, especially to solve the problems related to strategic decision-making, and its practicality is very wide [19]. The steps of AHP to deal with the problem are as follows:

(1) Establishing a hierarchical structure model.

(2) Establishing a comparative judgment model using the "expert scoring" method.

(3) Checking the consistency of the judgment matrix and ranking the weights of each factor.

Through analysis, we conclude that AHP, as a risk quantification method based on the subjective estimation of risk factors by risk analysts and relevant experts, has the following shortcomings when combined with practical problems: According to experimental psychology, nine variables are the psychological limit. When the number of risk factors is more than 9, the method estimated by experts is not feasible, and the result is unreliable. Experts usually answer the questions raised by risk analysts with words such as "about", "around", "up and down", and their information has great ambiguity. If the knowledge of classical mathematics is used to extract expert information, may cause the loss of information. The goal of the consistency of the judgment matrix is difficult to achieve, and the adjustment of $\lambda_{\max}$ consistency is blind.

The method of fuzzy mathematics fully considers the fuzziness of personal judgments, and overcomes the limitations of AHP and the subjectivity of human thinking by introducing the method of fuzzy mathematics. This qualitative and quantitative systematic combination of analysis method is called fuzzy analytic hierarchy process. Fuzzy Analytic Hierarchy Process calculates the combined weight of each level's constituent elements to the overall goal by clarifying the problem, establishing the analytic hierarchy structure model, constructing the judgment matrix, the level single ordering and the level total ordering five steps, so as to obtain the synthesis of different feasible schemes. Evaluation value. Similarly, we divide the aquifer water richness evaluation based on the fuzzy analytic hierarchy process into the following steps, that is, the identification of the main controlling factors of water richness, the construction of the analytic hierarchy process structure, and the construction and ranking of the fuzzy risk judgment matrix.

(b1) According to the analysis of the hydrogeological data of Hongliu Mine, five main controlling factors have been obtained, and the hierarchical structure model (Figure 1) shown in the following figure has been established:

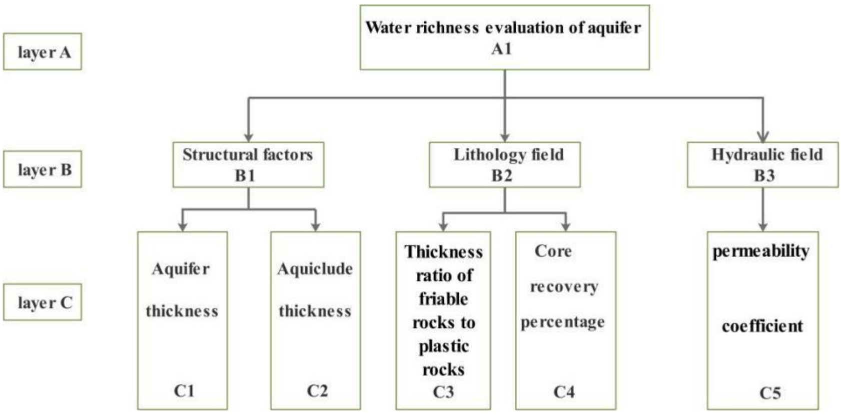


Figure 1. Hierarchical structure model diagram.

(b2) Construction of positive complementary judgment matrix.

The characteristics of the positive complementary judgment matrix: a_{ij} satisfies

$$0 \leqq a_{ij} \leqq 1 \tag{7}$$

$$a_{ij} + a_{ji} = 1 \tag{8}$$

$$a_{ii} = 0.5, \sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij} = \frac{n^2}{2} \tag{9}$$

In the positive complementary judgment matrix $\mathrm{A} = (a_{ij})_{n\times n}$

$$a_{ij} = \begin{cases} 0.5 & s_i = s_j \\ 1.0 & s_i < s_j \\ 0.0 & s_i > s_j \end{cases} \tag{10}$$

Among them, s_i, s_j represent the relative importance of indicators a_i and a_j respectively.

For layer B

$$\begin{array}{c} \\ B1 \\ B2 \\ B3 \end{array} \begin{array}{ccc} B1 & B2 & B3 \\ \left[\begin{array}{c} 0.5 \\ 0.3 \\ 0.4 \end{array}\right. & \begin{array}{c} 0.7 \\ 0.5 \\ 0.6 \end{array} & \left.\begin{array}{c} 0.6 \\ 0.4 \\ 0.5 \end{array}\right] \end{array}$$

For layer B1

$$\begin{array}{c|cc} & C1 & C2 \\ \hline C1 & 0.5 & 0.65 \\ C2 & 0.35 & 0.5 \end{array}$$

For layer B2

$$\begin{array}{c|cc} & C3 & C4 \\ \hline C3 & 0.5 & 0.7 \\ C4 & 0.3 & 0.5 \end{array}$$

For layer B3

$$\begin{bmatrix} C5 & 1 \end{bmatrix}$$

(b3) Write FUNCTION HANDLE based on the principle of FAHP method based on MATLAB language. According to the calculation steps and principles of FAHP, the line sum normalization method is adopted, and the function handle is written based on the MATLAB platform, and the weight ratio of the main control factors based on the FAHP analytic hierarchy process is calculated as shown in Table 2.

Table 2. Determine the weight of main control factors by FAHP.

Aquifer thickness	Aquiclude thickness	Thickness ratio of friable rocks to plastic rocks	Core recovery percentage	Permeability coefficient
0.2300	0.1700	0.1600	0.1067	0.3333

(c) Comprehensive weight:

The entropy method weight and the weight obtained by the fuzzy analytic hierarchy process are constrained by linear weighting to obtain the comprehensive weight:

$$W_j = \lambda W_j^1 + (1-\lambda) W_j^2 \tag{11}$$

In the formula: W_j is the comprehensive weight; W_j^1 is the entropy method weight; W_j^2 is the fuzzy analytic hierarchy process weight; λ *is* the preference coefficient, set to 0.5. The results of the comprehensive weight calculation are shown in Table 3.

The roof aquifer water inrush risk model is established according to the water richness index method, and the water inrush risk degree of the coal roof in Hongliu mining area is calculated, which is defined as the superimposed sum of the influence of the main control factors on a grid position of the mine working face.

$$CI = \sum_{k=1}^{n} W_k \cdot f_k(x, y) \tag{12}$$

In the formula: CI is the water richness index; W_k is the weight of influencing factors; n is the number of influencing factors; f_k is the single factor influencing value function.

Table 3. Comprehensive weight.

Aquifer thickness	Aquiclude thickness	Thickness ratio of friable rocks to plastic rocks	Core recovery percentage	Permeability coefficient
0.2033	0.1421	0.1252	0.1966	0.3328

3.2. Empirical formula to calculate roof fracturing zone

The "upper three zones" are formed above the mined-out area when the overlying rock strata are destroyed [20]. They are caving zone, fissure zone, and curved subsidence zone respectively. The caving zone and the fissure zone constitute the water channel formed by man-made mining damage. If the water channel enters and disturbs the overlying water-filled aquifer, such as the surface water body above the goaf, water accumulation in the goaf, etc. The height of the water fissure zone is greater than the distance between the surface water or aquifer and other water bodies and the mining face, it is a dangerous zone [21]. If the thickness of the overlying rock is greater than the height of the water-conducting fracture zone, the fracture zone cannot communicate with the aquifer and is a safe zone. Therefore, the degree of roof cracking can be quantitatively evaluated based on the height of the water-conducting fracture zone.

According to the empirical formula and the hydrogeological data of the mine, the overlying rock is medium-hard, and the corresponding formula is selected to calculate the height of the water-conducting fracture zone:

$$H_{li} = \frac{100\sum M}{1.6\sum M + 3.6} \pm 5.6 \tag{13}$$

In the formula: $\sum M$ is the cumulative mining thickness.

Calculated by formula 9, the development height of the water fracture zone in the Hongliu Coal Mine is shown in Table 4.

Table 4. Height value of water fracturing crack zone in Hongliu Coal Mine.

Drilling number	Height value	Drilling number	Height value	Drilling number	Height value
H911	17.13	H604	12.86	H201	28.07
H910	45.75	H603	43.53	H1808	66.82
H907	13.25	H602	47.92	H1807	50.43
H904	29.5	H601	43.78	H1805	69.81
H903	11.5	H506	51.21	H1802	72.63
H902	19.38	H504	9.18	H1801	49.85
H901	30.75	H503	18.3	H1708	57.79
H808	35	H502	57.16	H1707	71.26
H807	39.23	H501	25.33	H1706	75.94
H805	48.13	H407	45	H1704	70.2
H804	27.67	H405	37.19	H1702	39.75
H803	21.96	H403	41.6	H1701	60.87
H802	24.13	H402	34.37	H1611	67.13
H801	30.75	H401	57.75	H1610	51.02
H707	16.97	H306	49.02	H1609	48.13
H704	29	H301	56.38	H1607	75.63
H703	15.48	H208	61.81	H1605	69.08
H702	21.51	H204	32.79	H1603	71.24
H701	39.43	H203	65.61	H1602	75.91
H608	43.74	H202	69.82	H1601	64.8

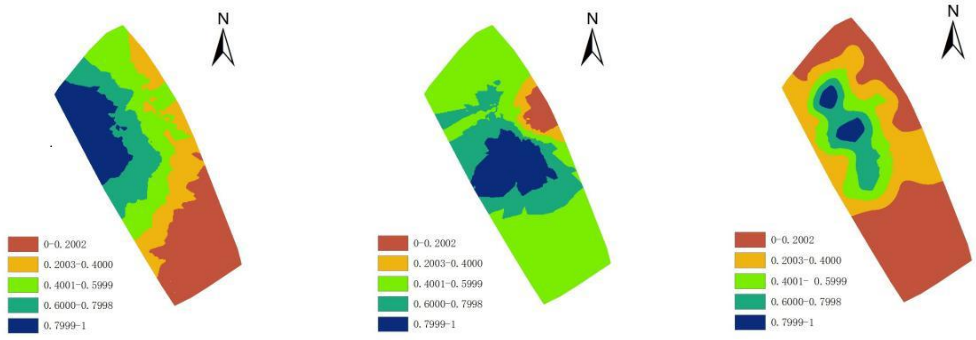
4. Establishment and composite superposition of thematic maps of roof water inrush

4.1. Introduction of GIS technology theory

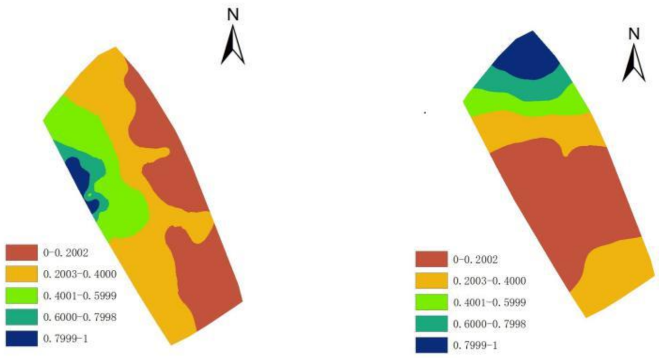
Geographic information system (GIS), is a member of the 3S system (GIS, GPS, and RS) [22]. It can integrate the unique visualization and geographical analysis functions of maps with a general database operation (e.g. statistical analysis, etc.). The main functions in the prediction of roof permeation are: collecting and storing the influencing factors of water inrush and establishing the corresponding database, drawing thematic maps of each influencing factor, coupling and weighting the relevant thematic maps with the water inrush prediction model to draw the roof water inrush risk zone map. This paper uses the EM-FAHP two-factor method to obtain the comprehensive weight of the main control factors, and uses the ArcGIS data spatial analysis function of analyzing and mining the known borehole data, effectively manage and integrate the database, and couple the thematic maps to obtain the water inrush risk area of the working face is divided and the coal roof water inrush risk evaluation model is established [23].

4.2. Thematic map of each main controlling factors

In order to eliminate the influence of different dimensions and orders of magnitude, the data of the main control factors of roof permeation obtained in the previous chapter are normalized, and the geographic information processing function of ArcGIS software is used to establish a thematic database of influence factors and use Kriging interpolation to determine the equivalent range. The natural breakpoint 5-level classification method is used to determine the threshold division to realize the visualization of the data. The thematic maps as shown in Figure 2.



(a) Aquifer thickness **(b)** Aquiclude thickness **(c)** Thickness ratio of friable rocks to plastic rocks



(d) Core recovery percentage **(e)** Permeability coefficient

Figure 2. Thematic map of each main controlling factor.

The aquifer thickness, aquiclude thickness, thickness ratio of friable rocks to plastic rocks, core recovery percentage and permeability coefficient are five main controlling factors. The weights are calculated by EM-FAHP and coupled by the multiplier normalization method, and the proportions are shown in the Figure 3 below:

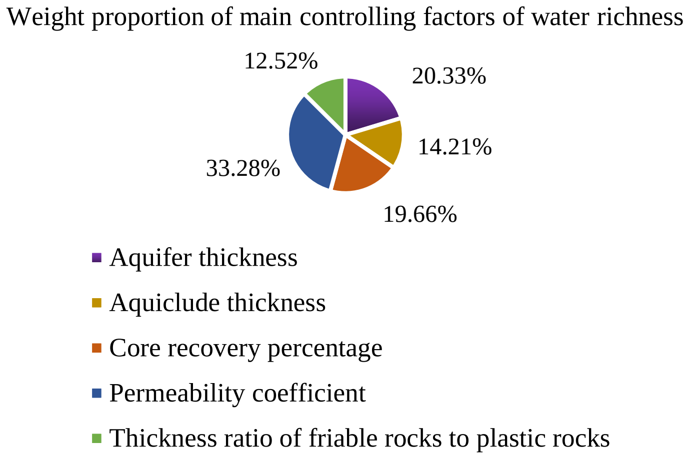


Figure 3. Thematic map of the weight proportion of main control factors.

The water-ricness index model established based on the factor weights determined by the EM-FAHP two-factor method, using the layer coupling function of ArcGIS to obtain the water-rich zone map (Figure 4).

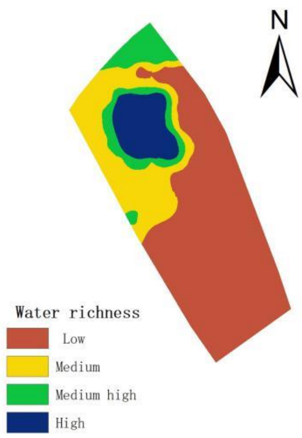


Figure 4. Water-richness zoning map of coal roofs.

The occurrence of roof permeation accidents is the comprehensive result of roof water-rich and water-conducting fractured zone development height [24]. In the upper three-zone theory, the water-conducting fracture zone is composed of caving zone and fracture zone, and its development pattern and maximum height are important indicators for the prediction and analysis of coal seam roof permeability [25]. According to the mine hydrogeological data, select the corresponding calculation formula and substitute it into the calculation. Through the ArcGIS layer interpolation function, the development of the water-conducting fracture zone can be highly visualized as shown in Figure 5.

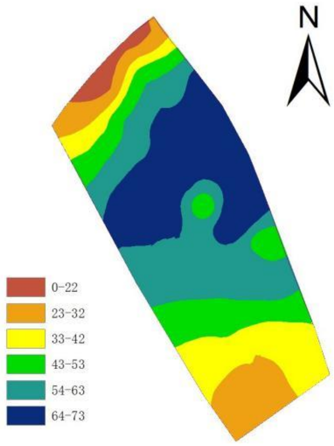


Figure 5. Thematic map of the development height of water-conducting fracture zone.

Superimpose the roof water-rich zone map with this map to realize the coupling of two necessary conditions, that is, whether the development degree of the water-conducting fracture zone communicates with the roof aquifer, and the roof water-rich degree determines the amount of water inrush [26]. Only when the roof water-conducting fracture zone is highly developed, communicating with the water-rich aquifer, and reaching a certain amount of water inrush, will the roof water inrush accident be triggered.

The layers of the two images are superimposed to obtain the zoning map of the permeable coal roof (Figure 6):

Figure 6. Comprehensive zone map of water inrush risk evaluation.

4.3. Comprehensive analysis of roof water inrush risk evaluation

The analysis of water inrush conditions in mining coal seams includes two aspects. One is the development height of the water-conducting fracture zone, whether the water-conducting fracture zone is connected to the roof aquifer, which is a necessary condition that affects the occurrence of roof water inrush, and the other is the water-richness of the roof aquifer of coal seam. From the water-rich zoning map, it can be seen that the water-rich water of Hongliu Minefield is stronger in the north-central and north, and weaker in the south and south-central. From the thematic map of the development height of the water-conducting fracture zone, it is known that the fractures are more developed in the central part, and the probability of conducting the aquifer is higher. It can be seen from the final comprehensive zoning map of the water inrush risk evaluation that the Hongliu minefield is divided into four areas as a whole: high safety zone, medium safety zone, medium-risk zone, and high-risk zone. The northern part is a high-risk area for water inrush, the central and northern part is a medium-risk zone, and the central and southern parts are high safety zone and medium safety zone for water inrush. Therefore, the roof water inrush risk in the Hongliu Minefield study area is higher in the north than in the south, and the central area is more dangerous than the surrounding areas.

4.4. Analysis and verification of roof penetration threat based on FLAC3D

4.4.1 Model establishment

For the roof water-inrush threat area obtained by the above method, FLAC^{3D} is used to verify and analyze the evaluation. According to the engineering background, a three-dimensional numerical model of roof permeation was established (Figure 7). The rock formation data of the roof and floor are shown in Table 5. The length, width and height of the model are respectively 300 m*200 m*150 m. The model has a total of 18,000 units and 20181 nodes. The working face is arranged along the coal seam incline, and mining is carried out along the coal seam direction, leaving a protective coal pillar of 50 m.

Table 5. Rock formation parameters.

Rock formation	Bulk modulus/(GPa)	Shear modulus/(GPa)	Cohesion /(MPa)	Internal friction angle/(°)	Tensile stress /(MPa)
Siltstone1	8	6	40	34	1.5
Mudstone1	6.5	10	20	25	1.5
Coarse sandstone	8	10	50	26	1.5
Siltstone2	6	9	40	28	1.5
Coal seam	3.2	4.5	20	36	1.5
Siltstone3	6	9	60	26	1.5
Mudstone2	8	9	60	25	1.5
Siltstone4	7	9	60	28	1.5
Aquifer	1	0.5	10	10	0.015
Fine sandstone	7	9	40	28	1.5

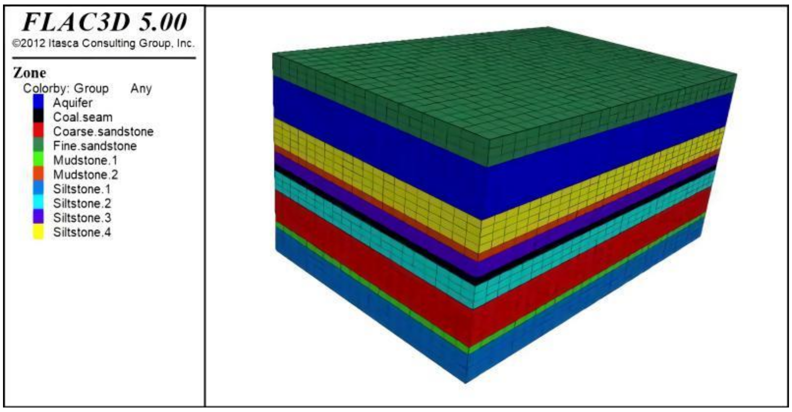


Figure 7. Three-dimensional numerical model.

4.4.2 Result analysis

According to the results of the numerical simulation, the water pressure distribution cloud map (Figure 8) and the plastic zone damage cloud map (Figure 9) were obtained during the excavation process. Because there are too many cloud images, some cloud images of typical working face excavation length are selected for analysis.

According to Figure 8, the water pressure rises continuously with the mining process, and the simulated water pressure distribution confirms the water-rich zoning of the coal mining workings obtained by using EM-FAHP two-factor coupling in the previous paper. In the simulated excavation, the development height of the water-conducting fracture zone was determined according to the damage cloud map of the plastic zone (Figure 9).

As the working face continues to advance and the area of the goaf increases, the plastic zone continues to advance, and the development of the water-conducting fracture zone increases. When advancing to about 200 meters, the height of the water-conducting fracture zone developed to the maximum height and stabilized, and the maximum height of the development of the water-conducting fracture zone was 50 meters. It is basically consistent with the height of the water conducting fracture zone in the danger zone calculated by the empirical formula. Therefore, numerical simulation of the excavation process of this working face can well prove the accuracy of the evaluation and analysis.

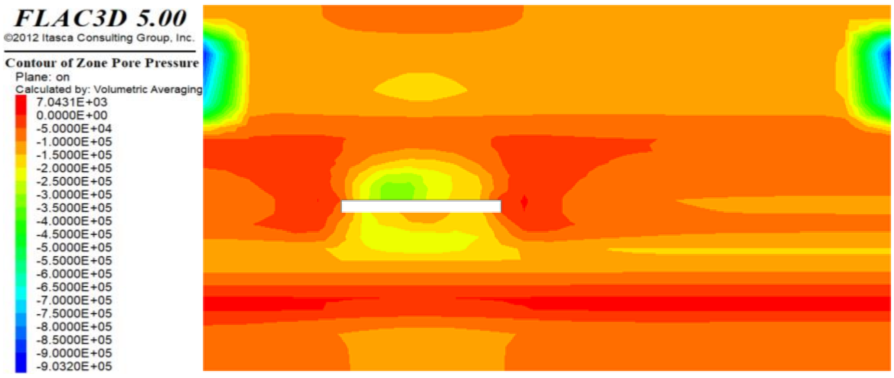
5. Prevention measures and research prospects

5.1. Prevention measures

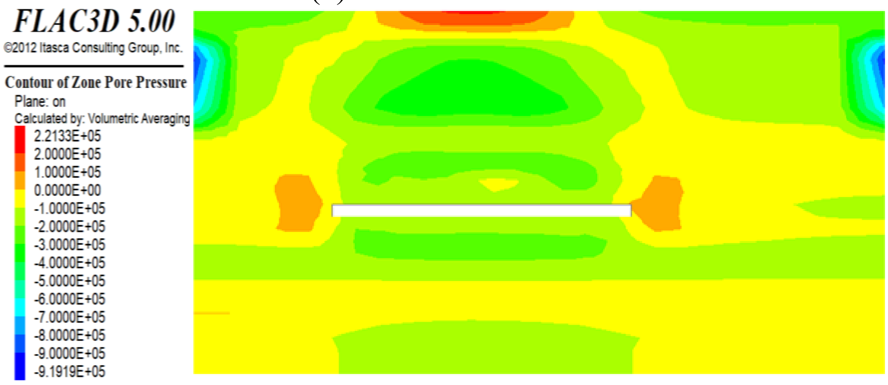
Based on the analysis of the main control factors and hydrogeological data of Hongliu Coal Mine roof permeation, combined with the relevant provisions of the Coal Mine Safety Regulations, the Mine Hydrogeological Regulations, and the Mine Water Control Work Regulations, the following prevention and control recommendations are proposed:

(1) Strengthen the observation of water level and pressure before mining, arrange observation points in the location of the top plate aquifer thickness, combine underground and surface, and establish a dynamic observation network to observe the changes of groundwater level.

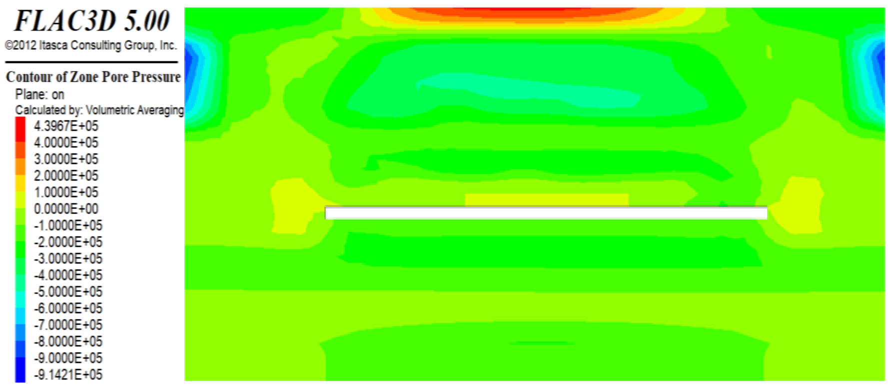
(a) Excavation 20 m.



(b) Excavation 80 m.



(c) Excavation 140 m.



(d) Excavation 200 m.

Figure 8. Cloud map of water pressure distribution.

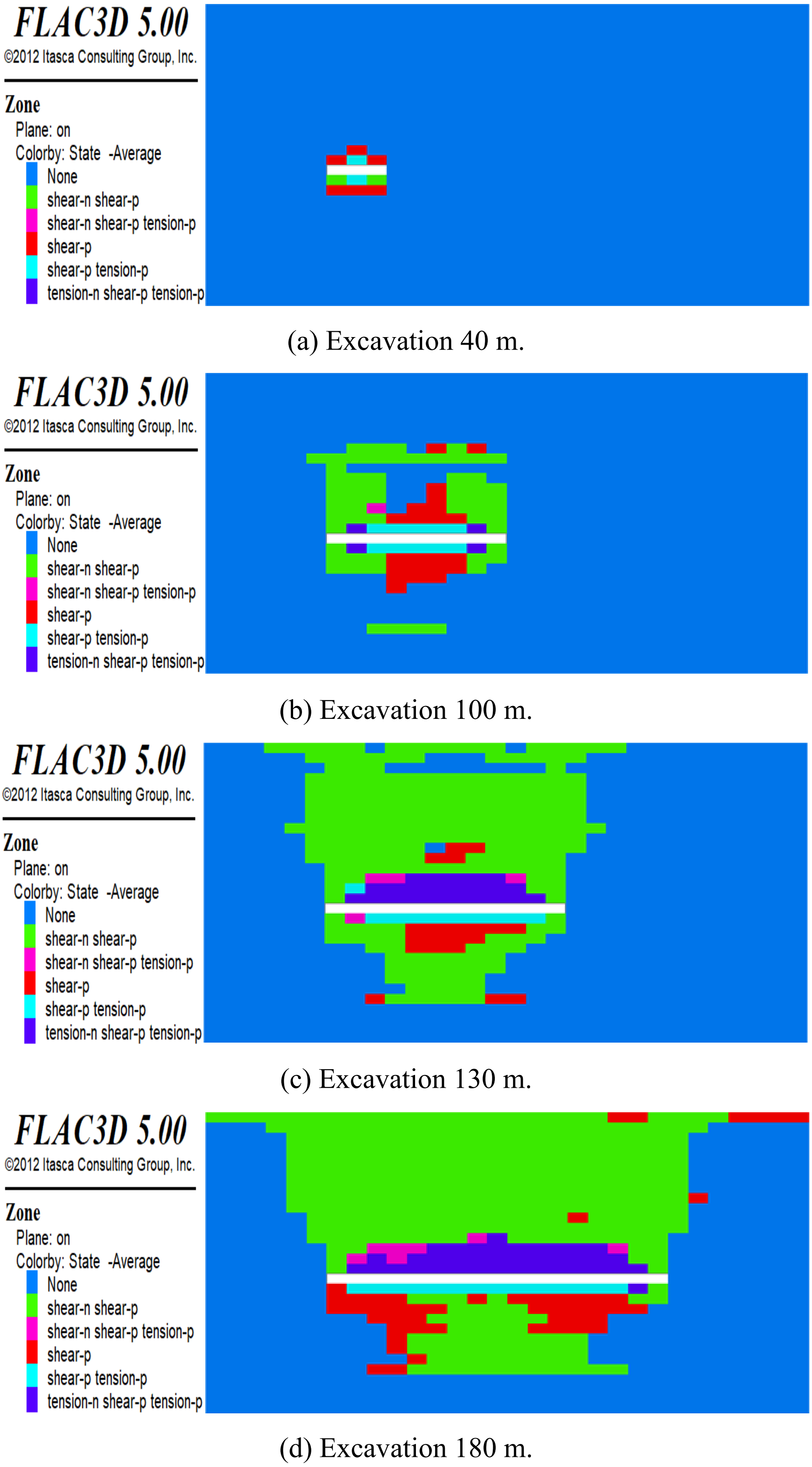


Figure 9. The damage cloud map of the plastic zone.

(2) Combine drilling and geophysical prospecting to prevent and control premining water damage,

prepare in advance the water pump and drainage pipes corresponding to the head, carry out joint drainage up and down the well or use the method of grouting to block water from the source.

(3) Use remote sensing and online systems to observe the changes in the amount of water of the main aquifers in real time, bury water pressure, water volume, water quality and other sensors in the dangerous area, and combine the expert system to give early warning.

(4) The fracture zone is relatively developed in the north-central part, with strong water richness, and large vertical deformation of the roof. Curtain grouting can be used to modify the water aquiclude to cut off the supply water source.

5.2. Research significance and prospects

Although this article uses GIS, theoretical analysis, numerical simulation, fuzzy mathematics and other multi-methods to conduct in-depth research and exploration on the coal roof water inrush risk and water inflow in the mining area. There are still many deficiencies in the research due to the data, time conditions and personal ability, which are specifically manifested in the following aspects:

(1) The data on the relevant control indicators of water richness in the mining area is relatively limited. Some areas of the mining area lack relevant borehole data. Therefore, the thematic map of each main control factor obtained by using the difference of borehole data is not accurate in some areas, and there are sudden changes and discontinuities in local areas. Although the final evaluation result can basically reflect the distribution law of regional water richness, there is still much room for improvement in data collection and interpolation processing.

(2) In the process of establishing the numerical model of the mining area, the generalization of some boundary conditions and source and sink terms is still not fine enough, and some hydrogeological parameters are not finely divided. Although the calculation results basically meet the accuracy requirements, there are still some errors with the actual situation.

6. Conclusions

This paper uses the theories and methods of mine geology, hydrogeology, geographic information system, data classification and other disciplines, adopting data collection, theoretical analysis, establishment of factor geological comprehensive model and other methods of coupling to study the influence of coal roof water richness factors ,establish a water-rich evaluation index system, and evaluate its water-rich and water inrush risk, which has guiding significance for mine water inrush prevention. The main results are as follows:

(1) According to the hydrogeological data of Hongliu Minefield, the main controlling factors of roof water inrush are collected from the aquifer thickness, aquiclude thickness, the thickness ratio of friable rocks to plastic rocks, core recovery percentage and permeability coefficient. Then the EM-AHP two-factor model is used to couple analyzes and processes data and establish a water-rich evaluation index system for coal roof aquifers.

(2) Standardization and normalization of the original data, using ArcGIS composite overlay geoscience information to obtain the coal roof water-rich evaluation zone, superimposing the roof cracking safety zone to realize the prediction of the roof water inrush risk zone of the study area.

(3) Using numerical simulation, FLAC^{3D} is used to simulate the possible water inrush area, and the numerical change in the mining process is simulated for rock plasticity and water pressure. It is

obtained that the location of the area with greater water inrush risk is just the central and northern region, which is in line with the evaluation analysis.

(4) In view of the risk zoning and the water richness of the aquifer of the study area, corresponding supporting prevention and control measures are proposed.

Data avaliability

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

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Conflicts of interest

The authors declare that they have no conflicts of interest.

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