Gray Evaluation of Water Inrush Risk in Deep Mining Floor

Xingyue Qu, Xiaoge Yu,* Xingwei Qu, Mei Qiu, and Weifu Gao

ABSTRACT: With the increase of the mining intensity of coal resources in China, the geological conditions of minefields have become more and more complex. The mining conditions of high pressure and high stress bring great challenges to the safe mining of coal resources. To accurately evaluate the risk of water inrush from the broken floor under high pressure and high stress, a gray evaluation model coupling the work breakdown structure (WBS), the risk-based supervision (RBS) theory, ordered binary comparison quantization method, and the center-point triangular whitenization weight function was proposed in this paper. Taking the No. 21 coal seam of Shanxi Formation in Guhanshan minefield as an example, studying the distribution characteristics of high pressure and high stress and the water inrush mechanism from the broken floor during No. 21 coal seam mining and analyzing the hydrochemical characteristics of the main water inrush aquifers below the No. 21 coal seam floor, this paper determined five main factors, including fault fractal dimensions, aquifer pressure, water-richness, destroyed floor depth, and effective aquiclude thickness. First, the work breakdown structure (WBS), the risk-based supervision (RBS) theory, and the ordered binary comparison quantization method were used to calculate the weight vectors of each index. Then, the center-point triangular whitenization weight function based on the work breakdown structure (WBS), the risk-based supervision (RBS) theory, and the ordered binary comparison quantization method were constructed to evaluate the water inrush risk from the broken floor under high pressure and high stress. Finally, the risk of water inrush from the broken floor during No. 21 coal seam mining in Guhanshan minefield was predicted using the gray evolution trend, which effectively reflects the risk characteristics of water inrush from the coal seam floor under high pressure and high stress. The results show that the evaluation and prediction results are consistent with the actual situation in Guhanshan minefield, which indicates that the model is suitable for evaluating and predicting the risk of water inrush from the broken floor under high pressure and high stress.

INTRODUCTION

Although areas of karst strata account for one quarter of the world’s continental areas, due to the differences of geological conditions and coal seam occurrence, there are no problems of floor water inrush in the process of coal seam mining in some countries, such as the United States, Canada, Australia, Germany, and the U.K. Only Hungary, Poland, Yugoslavia, and Spain are affected by the karst water in different degrees in the process of coal seam mining. In foreign countries, coal seams have been mined for more than 100 years; therefore, they are also the first to study the water inrush from the coal seam floor. In China, the research on floor water inrush started in the 1960s.1

China is a country with coal as its main energy source, and coal resource will still be the main energy source in China for a long time.2,3 In recent years, with the increase of coal mining depth in China, the mine geological conditions have become more and more complex and changeable.4,5 The problems of high pressure and high stress have become one of the major challenges restricting safe production of coal mines. For example, the 2131 working face of Hanwang Mine in the Jiaozuo mining area has developed minor structures and broken rock strata. After mining, the roof pressure destroys the strength of the floor aquiclude, and the floor water inrush occurs under the action of water pressure. The water bursting discharge reaches 900 m³/h, causing the working face to be flooded. The aquiclude below the 1441 working face of Wangfeng Mine in the Jiaozuo mining area is thin and the water pressure is high. In addition, the concentration of mine pressure at the initial stage of mining has damaged the compressive strength of the aquiclude. At the same time, the water pressure of L₈ limestone has not decreased significantly, resulting in many water inrush accidents in the mining face.

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with the water yield varying from 126 to 1680 m³/h. Therefore, it is of great theoretical significance and practical value to evaluate and predict the risk of water inrush from the broken floor under high pressure and high stress as accurately as possible for safe and efficient production of minefields.

In recent years, with the continuous development of science and technology, many scholars have studied the risk of water inrush from limestone karst aquifers during coal seam mining. For example, Shi used probability indexes to assess the risk of water inrush from the coal seam floor by quantitative main controlling factors. Wu put forward the construction of an evaluation index system and used the vulnerability index method to assess the risk of water inrush from the coal seam floor. Qiu used the fuzzy analytic hierarchy process (FAHP) and the gray correlation analysis to assess the risk of water inrush from limestone karst aquifers. The risk index model allowed for subdivision of the coal seam 13 floor area into two zones and four subzones, providing a more detailed scientific basis for safe production and control of water inrush. Based on GIS multisource information fusion technology, Zhu constructed a dimensionless model for water inrush risk assessment. Using the Fisher discriminant model, Zhang evaluated and predicted the water inrush risk from the coal seam floor. The above theories promote the rapid development of prevention and control technology of mine water disasters in China. However, due to the continuous increase of coal seam mining depth, a series of new changes have appeared in water inrush from the broken floor under the conditions of high pressure and high stress, and the prevention and control of water inrush have become more difficult. It is necessary to have a further understanding of the risk assessment, prediction, and prevention of water inrush from the coal seam floor. Guhanshan coal mine is located between the earthquake zone of North China Plain and the Fen-Wei earthquake zone and is greatly affected by the seismic activities of the two earthquake zones. The rock mass below the No. 21 coal seam is subjected to abnormal high stress in the horizontal direction. The sealing effect of karst cavities, the release pressure of the working face floor, and high stress acting on the coal seam floor lead to a higher water pressure of floor aquifers. As a result, in the joint and fault areas, the floor is broken extensively. Therefore, analyzing the law of water inrush from the No. 21 coal seam floor in Guhanshan minefield, this paper expounded the distribution characteristics of high pressure and high stress and the mechanism of water inrush from the broken floor. Combined with the hydrochemical characteristics of the main water inrush aquifers below the No. 21 coal seam floor, five main controlling factors, including fault fractal dimensions,

Figure 1. (A) Location map of Henan Province. (B) Location map of the Jiaozuo Mining Area in Henan Province. (C) Fault distribution in Guhanshan minefield.
aquifer pressure, water-richness, destroyed floor depth, and effective aquiclude thickness, were selected. The WBS-RBS evaluation index system was established, and the weight vectors of each index were calculated using the work breakdown structure, RBS theory, and the ordered binary comparison quantization method. Then, the center-point triangular whitenization weight function based on the work breakdown structure, RBS theory, and the ordered binary comparison quantization method was constructed to evaluate the water inrush risk from the broken floor under high pressure and high stress, and the risk of water inrush from the broken floor during No. 21 coal seam mining in Guhanshan minefield was predicted by the gray evolution trend.

MATERIALS AND METHODS

Study Area. The Guhanshan coal mine is located in the center of the Jiaozuo coalfield, about 25 km from Jiaozuo city, Henan province, in eastern China. The mine is irregularly developed, covering an area of around 17.00 km². It is located in the Cathaysian tectonic belts. The minefield has a monoclinic structure, with faults as the main structural form, as shown in Figure 1. According to the borehole data, the stratum in Guhanshan minefield consists of Ordovician (O), Carboniferous (C), Permian (P), Jurassic (J), Paleogene (E), and Quaternary (Q). Shanxi Formation and Taiyuan Formation of the Carboniferous-Permian are the main coal-bearing strata, and they include two minable coal seams. There are five coal seams in Shanxi Formation, only the No. 21 coal seam can be mined, and 11 coal seams in Taiyuan Formation, and only the No. 13 coal seam can be mined. Coal seam No. 21 is currently being mined.

The target coal seam for the risk assessment of floor water inrush is the No.21 coal seam. The No.21 coal seam is mineable throughout the field, with a thickness ranging from 3.15 to 6.27 m, with an average of 4.65 m. The aquifers in Guhanshan minefield mainly include the porous aquifer of Quaternary, the fissured aquifer of the Permian System, L8 limestone aquifer, L2 limestone aquifer, and the Ordovician limestone aquifer. Among them, the average distance between the No. 21 coal seam and the Quaternary strata is 290.93 m, and the Quaternary aquifer basically does not affect the minefield. The conditions of water recharging and runoff of the fissured aquifer of the Permian System above the No. 21 coal seam are poorer, and the water-richness is weaker. It is easy to be drained and generally does not cause mine water inrush. The thickness of the L8 limestone aquifer (below the No. 21 coal seam) ranges from 5.07 to 10.07 m, with an average thickness of 8.30 m. Karst fractures are developed in different sizes, with uneven water-richness. It is a direct water-filling aquifer for mining the No. 21 coal seam of Shanxi Formation. The thickness of the L2 limestone aquifer (below the L8 limestone aquifer) ranges from 5.90 to 21.62 m, with an average thickness of 12.57 m. Karst fractures are developed in different sizes, with uneven water-richness. It is an indirect water-filling aquifer for mining the No. 21 coal seam of Shanxi Formation. Karst fractures in Ordovician limestone (below the L2 limestone aquifer) are developed, and the water-richness is better. It is an indirect water-filling aquifer for mining the No. 21 coal seam of Shanxi Formation. However, with the changes of mining depth and mine pressure and structure, high pressure and high stress appear in the mining area, and the L2 limestone and Ordovician limestone aquifers also become the main prevention and control objects of mine water inrush.

Distribution Characteristics of High Stress. The stress of roof and floor is redistributed as the coal seam is mined, resulting in displacement, deformation, and even damage of rock mass. Under the action of mine pressure, the vertical abutment pressure is produced along the edge of the goaf and the high-stress concentration is large, as shown in Figure 2.17 The rear abutment pressure acts on the goaf, and the side abutment pressure acts on both sides of the coal wall. The front abutment pressure acts on the front of the working face,
and the pressure spike appears around the corner of the working face.

With the advancement of the working face, the rock mass near the open-off cut maintains the pressure relief state, and the load is redistributed in the goaf, giving rise to the floor rock mass in the expansion state (pressure relief-expansion stage). As the working face continues to advance, due to the reduction of the mine pressure intensity, the rock mass above the goaf gradually falls, and the rock mass below the coal seam is gradually recompressed, returning to a new equilibrium condition (compression-stability stage). Therefore, the rock mass below the coal seam repeatedly changes in three stages, compression, expansion, and recovery, as shown in Figure 3. At the boundary of the compression and expansion zones, the floor rock mass is prone to shearing failure. Bed-separated fissures and vertical fractures usually exist in the floor rock mass in the expansion state. Therefore, the floor rock mass around the marginal zone of the coal pillar is easy to be damaged due to its developed fractures. Besides, under the action of horizontal and vertical stresses, there is often a heaving floor in the middle of the expansion zone, and the strike of the heaving floor is consistent with that of the working face, which indicates that a damaged floor is caused by horizontal abnormal tectonic stress.

According to the theory of mine pressure, there may be three types of pressure acting on coal seams, including both existing internal and external stress fields, existing plastic zone, and single elastic distribution. If the distribution of abutment pressure is approximately simplified as uniform load (Figure 4), the abutment stress at any point of the rock mass below the coal seam can be calculated according to the elasticity theory. Taking the plastic distribution as an example, the sum of the stresses acting at any point of the rock mass below the coal seam is calculated.

According to the elasticity theory, assuming that the floor rock mass is elastic stratum and the abutment pressure acting on the floor rock mass is regarded as the plane load, the sum of the stresses produced by the distributed loads on any point \( M(x, z) \) (Figure 4) under the floor is the stress \( (\sigma_x, \sigma_y, \tau_{xy}) \) acting at point \( M(x, z) \); therefore, the principal stress acting at point \( M(x, z) \) is \( \sigma_1 \) and \( \sigma_3 \)

\[
\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}
\]

\[
\sigma_3 = \frac{\sigma_x + \sigma_y}{2} - \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}
\]

**Distribution Characteristics of High Pressure.** When the coal seam is not mined, the water pressure of the \( L_8 \) limestone, \( L_2 \) limestone, and Ordovician limestone aquifers generally depends on their water head height. Taking the

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**Figure 4.** Simplified model of the abutment pressure.

**Figure 5.** Abnormal high pressure affected by mining.

**Figure 6.** Stress analysis of the goaf floor.
shallow aquifer as an example, its hydraulic gradient value is relatively small, which causes its water pressure to be low. But with the increase of the buried depth of the aquifer, the water pressure also increases. However, as the coal seam is mined, the stress of the roof is redistributed, and its own weight is transferred to the coal pillar, forming abutment stress higher than the original stress (Figure 2). When the increased abutment stress is transmitted to the karst water cavity, the karst water cavity is compressed, resulting in a smaller groundwater storage space and an obvious increase of the water pressure. At the same time, if the water inlet and the water outlet of the karst water cavity are also blocked by sediment particles brought by a current, a closed water-filled cave is formed, leading to a sharp increase of water pressure. Because of the incompressibility of water, it can transmit all of the pressure acting on itself in all directions according to the original size. As a result, the rock mass below the coal seam is compressed by abutment pressure, similar to the principle of “hydraulic press”. The water pressure can reach the maximum of abutment pressure, that is, $K_{\text{max}}\gamma H$, where $K_{\text{max}}$ is the concentration index of the abutment pressure, $\gamma$ is the average bulk density of strata, and $H$ is the mining depth. The diagrammatic sketch of the abnormally high pressure during No. 2 coal seam mining is shown in Figure 5.

Mechanism of Water Inrush from the Broken Floor under High Pressure and High Stress. Guanshan minefield is located between the earthquake zone of the North China Plain and the Fen-Wei seismic belt, with active tectonic movement. The geological structure of the mining area is obviously controlled by the principal stress in the NEE-SWW direction, and it is obtained from the stress analysis of the goaf floor, as shown in Figure 6. When the roof does not collapse, in the vertical direction, the pressure of the roof does not act on the goaf floor, and the floor is in a state of pressure relief. As a result, the goaf floor is mainly affected by the tectonic stress in the NEE-SWW direction, namely, horizontal stress, high pressure of the L8 limestone aquifer, and the expansion force of floor strata. Therefore, during the mining of No. 21 coal seam of Shanxi Formation in Guanshan minefield, the concentrated high stress acting on the coal seam floor in the horizontal direction caused the development of small-sized faults and joints in the rock mass below the coal seam floor. As mining of the No. 21 coal seam is continued, the rock mass below the coal seam is compressed by abutment pressure, and the water pressure can reach the maximum of abutment pressure. Under the condition of abnormally high pressure, the maximum horizontal principal stress acting on the coal seam floor is greater than its uniaxial compressive strength, easily

Figure 7. Water inrush model of fault activation.

Figure 8. Water inrush model of fracture coalescence.
resulting in the damage failure of the rock mass below the coal seam floor and then causing water inrush accidents. The water inrush mode is shown in Figures 7 and 8.

**Hydrochemical Characteristics of the L8 Limestone Aquifer.** As shown in Figure 9, the distribution of L8 limestone water samples is relatively discrete in the square projection area, mainly distributed in the zones of No. 1, No. 3, and No. 5. The content of the alkaline-earth metal is higher than that of the alkali metal, and the content of weak acid is higher than that of strong acid, with the hardness of carbonic acid being higher than 50%. The hydrochemistry types include HCO₃⁻-Ca, HCO₃⁻-K + Na, HCO₃⁻-Ca·Mg, SO₄²⁻-Mg-K + Na, HCO₃⁻-Mg, HCO₃⁻-Ca-K + Na, and HCO₃⁻-K + Na·Mg. Among them, 25 water samples are HCO₃⁻-Ca and 18 water samples are HCO₃⁻-K + Na. Both are the main hydrochemistry types of the L8 limestone aquifer, accounting for 74% of the total number. The pH ranges from 7 to 8, with weak alkalinity. The content of TDS is relatively stable, mainly about 500 mg/L, and a few samples are more than 1000 mg/L, which implies that the water quality is good.

**Hydrochemical Characteristics of the L2 Limestone Aquifer.** As shown in Figure 9, the L2 limestone water samples are concentrated in the square projection area, all of which are distributed in the zones of No. 1, No. 3, and No. 5. The content of the alkaline-earth metal is higher than that of the alkali metal, and the content of weak acid is higher than that of strong acid, with the hardness of carbonic acid being higher than 50%. The hydrochemistry types of all water samples are HCO₃⁻-Ca, which is the main hydrochemistry type of the L2 limestone aquifer. The pH ranges from 7.1 to 8.4, with weak alkalinity. The content of TDS is relatively stable, mainly about 350 mg/L, and a few samples are less than 300 mg/L, which implies that the water quality is good.

**Hydrochemical Characteristics of the Ordovician Limestone Aquifer.** As shown in Figure 9, the Ordovician limestone water samples are concentrated in the square projection area, all of which are distributed in the zones of No. 1, No. 3, and No. 5. The content of the alkaline-earth metal is higher than that of the alkali metal, and the content of weak acid is higher than that of strong acid, with the hardness of carbonic acid being higher than 50%. The hydrochemistry types of all water samples are HCO₃⁻-Ca, which is the main hydrochemistry type of the Ordovician limestone aquifer. The pH ranges from 7.6 to 8.4, with weak alkalinity. The content of TDS is relatively stable, mainly about 300 mg/L, and a few samples are more than 400 mg/L, which implies that the water quality is good.

Through the above analysis, it can be seen that the water quality of L2 limestone water samples is similar to that of Ordovician limestone water samples, and their hydrochemistry types are both HCO₃⁻-Ca, while there are some differences between L8 limestone water samples, L2 limestone water...
Figure 10. Contour map of the fault fractal dimension.

Figure 11. Contour maps of the pressure of main water-filling aquifers below the No. 21 coal seam.
samples, and Ordovician limestone water samples. Therefore, we regard the L8 limestone aquifer as a relatively independent aquifer system and believe that there is a close hydraulic connection between the L2 limestone aquifer and the Ordovician limestone aquifer, that is to say, it is regarded as a water-bearing rock series with a unified hydraulic connection.

## RESULTS

**Main Controlling Factors.** The risk assessment of water inrush from the broken floor under high pressure and high stress is no longer a simple assessment by the water inrush coefficient. Based on the distribution characteristics of high pressure and high stress and analyzing the mechanism of water inrush from the broken floor under high pressure and high stress during No. 21 coal seam mining, this paper selected five main factors, including fault fractal dimensions, aquifer pressure, water-richness, destroyed floor depth, and effective aquiclude thickness, for the assessment of water inrush from the broken floor under high pressure and high stress during No. 21 coal seam mining. According to the results of the above hydrochemical analysis between different aquifers, the L8 limestone aquifer is regarded as a relatively independent aquifer system, and we believe that there is a close hydraulic connection between the L2 limestone aquifer and the Ordovician limestone aquifer; that is to say, it is regarded as a water-bearing rock series with a unified hydraulic connection.

**Fault Fractal Dimensions.** The structural feature of Guanshan minefield is mainly fault, which is the external display of high stress in Guanshan minefield. The more complex the fault is, the more broken the floor rock mass is, which implies higher stress. The fault fractal dimension is based on the faults below the coal seam floor, using the fractal geometry method and selecting the information dimension of the fault area to carry out fractal quantitative research on the fault system, which can better reflect the complexity of the faults and be used as an important index for the risk assessment.

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**Figure 12.** Comprehensive zone maps of the water-richness of main water-filling aquifers below the No. 21 coal seam.

**Figure 13.** Division model of the floor failure characteristics during No. 21 coal seam mining.
of water inrush from the broken floor under high pressure and high stress.19,20

In this paper, taking the faults below the No. 21 coal seam of Shanxi Formation as the research object, the affected area of faults exposed when mining the No. 21 coal seam is divided into several square areas by using square grids (200 × 200), and the fault fractal dimension is carried out for each square area, obtaining a contour map of fault fractal dimension (Figure 10). The thresholds are 0.7, 1.1, and 1.5, which implies that the fault fractal dimension is large near the fault zone.

Aquifer Pressure. Generally, the deeper the coal seam is buried, the larger is the aquifer pressure acting on the coal seam floor. Under the joint action of hydrostatic pressure and hydrodynamic pressure, the aquifer pressure causes deformation and failure of the rock mass below the coal seam floor, which further widens the original structural cracks or produces

Figure 14. Numerical simulation.

Figure 15. Contour map of the destroyed floor depth.
Figure 16. Sketch map of effective aquiclude.

Figure 17. Contour map of the effective thickness of aquiclude below the No. 21 coal seam floor.
new structural cracks. This action enhances the water transmissibility of the water inrush passageway and weakens the strength of the confining beds located in the coal seam floor. The water-resisting ability of the floor confining beds decreases, which causes the occurrence of water inrush from a coal seam floor. Therefore, the aquifer pressure as a main controlling factor for the risk assessment of water inrush from the broken floor under high pressure and high stress is of great significance. According to the borehole data of the research area, it can be found that the pressure of the aquifer below the coal seam floor is more than 6 MPa in the whole minefield. The contour maps of the L8 limestone aquifer pressure and the L2 limestone–Ordovician limestone aquifer pressure are shown in Figure 11.

Aquifer Water-Richness. Under the mining conditions of high pressure and high stress, the water-richness of the aquifers below the coal seam floor is directly related to the water bursting discharge. Therefore, it is very important to zone the

Table 1. Relative Importance of Evaluation Indicators

| evaluation indicators | R1 | R2 (MPa) | R3 | R4 (m) | R5 (m) |
|-----------------------|----|----------|----|--------|--------|
| R1                    | 0.5| 1        | 1  | 1      | 1      |
| R2 (MPa)              | 0  | 0.5      | 1  | 1      | 1      |
| R3                    | 0  | 0        | 0.5| 0      | 1      |
| R4 (m)                | 0  | 1        | 0  | 0.5    | 1      |
| R5 (m)                | 0  | 0        | 0  | 0      | 0.5    |

Table 2. Judgment Matrix

| P   | P1 | P2 | P3 | P4 | P5 |
|-----|----|----|----|----|----|
| p1  | 1  | 1/2| 1/6| 1/4| 1/8|
| p2  | 2  | 1  | 1/4| 1/2| 1/6|
| p3  | 6  | 4  | 1  | 2  | 1/2|
| p4  | 4  | 2  | 1/2| 1  | 1/4|
| p5  | 8  | 6  | 2  | 4  | 1  |

Table 3. Antisymmetric Matrix

| Q   | q1 | q2 | q3 | q4 | q5 |
|-----|----|----|----|----|----|
| q1  | 0  | -0.301 | -0.778 | -0.602 | -0.903 |
| q2  | 0.301 | 0     | -0.602 | -0.301 | -0.778 |
| q3  | 0.778 | 0.602 | 0     | 0.301 | -0.301 |
| q4  | 0.602 | 0.301 | -0.301 | 0     | -0.602 |
| q5  | 0.903 | 0.778 | 0.301 | 0.602 | 0     |

Table 4. Matrix G

| G  | g1 | g2 | g3 | g4 | g5 |
|----|----|----|----|----|----|
| g1 | 1  | 0.574 | 0.161 | 0.304 | 0.093 |
| g2 | 1.741 | 1 | 0.280 | 0.530 | 0.161 |
| g3 | 6.207 | 3.565 | 1 | 1.888 | 0.574 |
| g4 | 3.288 | 1.888 | 0.530 | 1 | 0.304 |
| g5 | 10.808 | 6.207 | 1.741 | 3.288 | 1 |

Table 5. Weights of Evaluation Indicators Calculated by the Sum-Product Method

| evaluation indicators | R1 | R2 (MPa) | R3 | R4 (m) | R5 (m) |
|-----------------------|----|----------|----|--------|--------|
| weights (W_a)         | 0.250 | 0.224 | 0.174 | 0.197 | 0.155 |

Table 6. Weights of Evaluation Indicators Calculated by the Square Root Method

| evaluation indicators | R1 | R2 (MPa) | R3 | R4 (m) | R5 (m) |
|-----------------------|----|----------|----|--------|--------|
| weights (W_b)         | 0.469 | 0.269 | 0.076 | 0.143 | 0.043 |
water-richness of the water-bearing rock series with high pressure below the coal seam floor for risk assessment and prediction of water inrush from the broken floor. In this paper, an information fusion model for the water-richness assessment of the L8 limestone aquifer and the L2 limestone–Ordovician limestone aquifer was constructed based on four main factors, namely, water inflow of drilling, the aquifer thickness, core rate of drilling, and the fault influencing factor. The comprehensive zone maps of water-richness for the L8 limestone aquifer and the L2 limestone–Ordovician limestone aquifer were drawn, as shown in Figure 12. It can be seen from Figure 12 that the distribution law of water-richness for the L8 limestone aquifer is uneven, but on the whole, it is inclined to medium water-richness or strong water-richness. The water-richness of the L2 limestone–Ordovician limestone aquifer is better, which belongs to the strong water-richness area in general, and easy to induce accidents of water inrush from the coal seam floor under the action of high pressure and high stress.

Table 7. Relation between the Tone Operators and Relative Weights

| tone operators | same | a little | slightly | obviously | more obviously | prominently |
|----------------|------|----------|----------|-----------|---------------|------------|
| relative weights | 1.0  | 0.905    | 0.818    | 0.739     | 0.667         | 0.60       |
|                 | 0.60 | 0.538    | 0.481    | 0.429     | 0.379         | 0.333      |

Table 8. Weight Matrix Determined by the Ordered Binary Comparison Quantization Method Coupled with the Work Breakdown Structure and the RBS Theory

| evaluation criteria | evaluation indicators | low risk | medium risk | high risk | extremely high risk |
|---------------------|-----------------------|----------|-------------|-----------|---------------------|
| R1                  | 0.35                  | 0.9      | 1.3         | 1.75      |                     |
| R2                  | 0.875                 | 1.75     | 3.375       | 5.125     |                     |
| R3                  | 0.125                 | 0.375    | 0.625       | 0.875     |                     |
| R4                  | 2.5                   | 7.5      | 12.5        | 17.5      |                     |
| R5                  | 7.5                   | 22.5     | 37.5        | 52.5      |                     |

Table 9. Weights of Evaluation Indicators for the Risk Assessment of Water Inrush from the L8 Limestone Aquifer during No. 21 Coal Seam Mining in Guhanshan Minefield

| risk of L8 limestone aquifer for the water inrush during No. 21 coal seam mining W* = 0.618 |
|-----------------------------------------------|-----------------------------------------------|
| R11               | R12               | R13               | R14 (m) | R15 (m) |
| hierarchy weights | 0.386             | 0.233             | 0.119   | 0.168   | 0.094             |
| combined weights  | 0.239             | 0.144             | 0.074   | 0.104   | 0.058             |

Table 10. Weights of Evaluation Indicators for the Risk Assessment of Water Inrush from the L2 Limestone–Ordovician Limestone Aquifer during No. 21 Coal Seam Mining in Guhanshan Minefield

| Risk of L2 limestone–Ordovician limestone aquifer for the water inrush during No. 21 coal seam mining W* = 0.382 |
|---------------------------------------------------------------|---------------------------------------------------------------|
| R21               | R22               | R23               | R24 (m) | R25 (m) |
| hierarchy weights | 0.386             | 0.233             | 0.119   | 0.168   | 0.094             |
| combined weights  | 0.147             | 0.089             | 0.045   | 0.064   | 0.035             |

Table 11. Center Points of Each Gray Classification

| evaluation criterion | evaluation indicators | low risk | medium risk | high risk | extremely high risk |
|---------------------|-----------------------|----------|-------------|-----------|---------------------|
| water inrush risk for the L8 limestone aquifer |
| R11                | 0.35                  | 0.9      | 1.3         | 1.75      |                     |
| R12                | 0.875                 | 1.75     | 3.375       | 5.125     |                     |
| R13                | 0.125                 | 0.375    | 0.625       | 0.875     |                     |
| R14                | 2.5                   | 7.5      | 12.5        | 17.5      |                     |
| R15                | 7.5                   | 22.5     | 37.5        | 52.5      |                     |
| water inrush risk for the L2 limestone–Ordovician limestone aquifer |
| R21                | 0.35                  | 0.9      | 1.3         | 1.75      |                     |
| R22                | 1.15                  | 2.45     | 2.75        | 3.05      |                     |
| R23                | 0.125                 | 0.375    | 0.625       | 0.875     |                     |
| R24                | 2.5                   | 7.5      | 12.5        | 17.5      |                     |
| R25                | 46.5                  | 51.5     | 56.5        | 61.5      |                     |

Figure 19. Sketch map of the center-point triangular whitenization weight function.
mine pressure, forming obvious water flowing channels. In this paper, a three-dimensional finite difference program in Flac3D is used to simulate the destroyed floor depth during No. 21 coal seam mining under high pressure and high stress, and the model size is 400 × 216 × 600. First, the self-weight stress of the rock mass is calculated to obtain the primary stress field, and all nodal displacements are assigned to zero and the stress field is retained. Taking 20 meters as a step to push forward in the x-axis direction, the destroyed floor depth is simulated. The initial stress equilibrium state of the model is shown in Figure 14a, and the simulation results are shown in Figure 14b.

It can be seen from Figure 14 that the maximum destroyed floor depth is 7.2 m in the early mining period (20 m). The maximum destroyed floor depth gradually increases to 12.6 m with continuous mining. As the No. 21 coal seam is mined continuously to the 120 m level, the plastic zone occurred in the floor, and the maximum destroyed floor depth was stable up to 18.76 m until the mining depth was up to 400 m. The contour map of the destroyed floor depth is shown in Figure 15.

Effective Aquiclude Thickness. The effective aquiclude is the protective rock mass below the broken zone and above the original water flowing crevice zone. The effective thickness of the aquiclude is the difference between the thickness of the aquiclude and the thickness of the broken zone and the original water flowing crevice zone (Figure 16). Under mining conditions of high pressure and high stress, the effective aquiclude is the main factor for resisting water inrush from the karst aquifer, and it is an important index to assess the risk of water inrush from the broken floor.

Figure 17 shows the contour map of the effective thickness of aquiclude below the No. 21 coal seam in Guhanshan minefield. In the mining area, taking the effective thickness of aquiclude within the range from the No. 21 coal seam floor to the L8 limestone aquifer roof and the effective thickness of aquiclude within the range from the L8 limestone aquifer floor to the L1 limestone−Ordovician limestone aquifer roof as an example, both gradually become thinner from west to east, but there are also several areas with the local thickness increasing suddenly. As a result, under similar conditions of water pressure and complexity of geological structures and other factors, the thinning of effective aquiclude leads to an increased risk of water inrush from the broken floor.

Risk Assessment. Evaluation Index System with the Work Breakdown Structure and the Risk-Based Supervision Theory (WBS-RBS Theory). According to the analysis of main controlling factors of water inrush from the No. 21 coal seam floor under the mining conditions of high pressure and high stress in Guhanshan minefield, the WBS-RBS evaluation index system for the risk assessment of water inrush from the broken floor was constructed, as shown in Figure 18.

Index Weight Calculation Based on WBS-RBS-Ordered Binary Comparison Quantization Method. First, two decision-making experts were invited to make pairwise comparisons among five main controlling factors, and the comparison matrix $R$, which is based on the relative importance, was obtained. The results are shown in Table 1.

| $\lambda_1^0$ | 0.2 | 0.4 | 0.06 | 1 | 4 | 0.2 | 0.6 | 0.06 | 1 | 23 |
| $\lambda_2^0$ | 2 | 6 | 1 | 20 | 60 | 2 | 4 | 1 | 20 | 65 |
| actual values | 0.7 | 1.2 | 0.38 | 16 | 37 | 0.7 | 2.3 | 0.35 | 16 | 50 |

**Table 12. Extension Values and Actual Values of Each Indicator**

| $R_{ij}$ | $R_{ij}^1$ | $R_{ij}^2$ | $R_{ij}^3$ | $R_{ij}^4$ | $R_{ij}^5$ | $R_{ij}^1$ | $R_{ij}^2$ | $R_{ij}^3$ | $R_{ij}^4$ | $R_{ij}^5$ |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| $R_{11}$  | 0.364     | 0.629     | 0.000     | 0.000     | 0.000     | 0.364     | 0.115     | 0.100     | 0.000     | 0.300     |
| $R_{12}$  | 0.636     | 0.371     | 0.980     | 0.000     | 0.030     | 0.636     | 0.885     | 0.900     | 0.000     | 0.700     |
| $R_{13}$  | 0.000     | 0.000     | 0.020     | 0.300     | 0.970     | 0.000     | 0.000     | 0.000     | 0.300     | 0.000     |
| $R_{14}$  | 0.000     | 0.000     | 0.000     | 0.700     | 0.000     | 0.000     | 0.000     | 0.000     | 0.700     | 0.000     |

**Table 13. Whitenization Convergence Coefficients**

**Figure 20. Sketch map of the evaluation objective.**

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The extension values and actual values of each indicator are shown in Table 12. The whitenization convergence coefficients are shown in Table 13.
\[ R = (r_{ij})_{n \times n} = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{pmatrix} \]

where \( r_{ij} \) is defined as:

\[ r_{ij} = \begin{cases} 
0, & \text{if indicator } u_i \text{ is less important than indicator } u_j \\
1/2, & \text{if indicator } u_i \text{ is as important as indicator } u_j \\
1, & \text{if indicator } u_i \text{ is more important than indicator } u_j
\end{cases} \quad \text{and} \quad r_{ji} = 1 - r_{ij} \]

when \( r_{ij} = 1/2 \), it implies that the indicator \( u_i \) is of the same importance as itself.

According to the comparison matrix \( R \), the importance ranking index \( z_i \) of each evaluation indicator was solved:

\[ z_i = \sum_{j=1}^{n} (2r_{ij}) = 2 \sum_{j=1}^{n} r_{ij}, \quad i, j = 1, 2, \ldots, n \]

The judgment matrix \( P \) was constructed based on the importance ranking index \( z_i \) as shown in Table 2.

\[ P = [p_{ij}]_{n \times n} = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{pmatrix} \]

where \( p_{ij} = \begin{cases} 
z_i - z_j, & z_i > z_j \\
1/z_i - z_j, & z_i < z_j
\end{cases} \quad \text{Assuming } Q = \log P = \frac{1}{\log(z_i - z_j)} \quad \text{we calculated the antisymmetric matrix } Q_k \]

\[ \text{(1) Sum-product method: } G = [g_{ij}]_{n \times n} = \prod_{k=1}^{n} W_k \]

\[ \text{(2) Square root method: } G = [g_{ij}]_{n \times n} = \sqrt{ W_i^\top W_j } \]

\[ \text{(3) Series binary comparison method: } \]

The importance ranking index set \( R^* = \{R_1, R_2, R_3, R_4, R_5\} \) was solved based on the ranking index \( z_i \). Taking \( R_1 \) as a criterion, we compared the relative importance between \( R_1 \) and \( R_2 \), \( R_1 \) and \( R_3 \), \( R_2 \) and \( R_4 \), and \( R_3 \) and \( R_5 \) using the series binary comparison method. The fuzzy tone operators were judged to be obviously, slightly, slightly, and slightly, respectively. Based on the relation between the tone operators and relative weights (Table 7), the weight vector \( W_k \) was calculated using the formula \( \phi_{ik} = \phi_{i(l-1)} \cdot \phi_{(l-1)} \)

\[ W_k = (0.429, 0.286, 0.191, 0.127) \]

After normalization, the weight vector of evaluation indicators was obtained by the series binary comparison method as follows

\[ W = (0.492, 0.211, 0.094, 0.141, 0.062) \]

Weight decision-making was conducted (as shown below) by the geometric averaging operator.

\[ W = \left( \prod_{i=1}^{f} W_i \right)^{1/3} \]

The decision weight vector of evaluation indicators is as follows:

\[ W = (W_1 \times W_2 \times W_3)^{1/3} = (0.386, 0.233, 0.119, 0.168, 0.094) \]

Pairwise comparison matrices \( R^*_k \) based on the relative importance of five evaluation indicators for the L8 limestone aquifer and the L2 limestone-Ordovician limestone aquifer were calculated as follows

\[ R_1^* = \begin{pmatrix} 1/2 & 1 \\ 0 & 1/2 \end{pmatrix} \quad R_2^* = \begin{pmatrix} 1/2 & 1 \\ 0 & 1/2 \end{pmatrix} \quad R_3^* = \begin{pmatrix} 1/2 & 1 \\ 0 & 1/2 \end{pmatrix} \]

\[ R_4^* = \begin{pmatrix} 1/2 & 1 \\ 0 & 1/2 \end{pmatrix} \]

Judgment matrices \( P^*_k \) based on the importance ranking index were calculated as follows

\[ P_1^* = \begin{pmatrix} 1/2 & 1 \\ 0 & 2/1 \end{pmatrix} \quad P_2^* = \begin{pmatrix} 1/2 & 1 \\ 0 & 2/1 \end{pmatrix} \quad P_3^* = \begin{pmatrix} 1/2 & 1 \\ 0 & 2/1 \end{pmatrix} \quad P_4^* = \begin{pmatrix} 1/2 & 1 \\ 0 & 2/1 \end{pmatrix} \]

Antisymmetric matrices \( Q^*_k \) based on the importance ranking index were calculated as follows

\[ Q_1^* = \begin{pmatrix} 0 & -0.301 \\ 0.301 & 0 \end{pmatrix} \quad Q_2^* = \begin{pmatrix} 0 & -0.301 \\ 0.301 & 0 \end{pmatrix} \quad Q_3^* = \begin{pmatrix} 0 & -0.301 \\ 0.301 & 0 \end{pmatrix} \]

\[ Q_4^* = \begin{pmatrix} 0 & -0.301 \\ 0.301 & 0 \end{pmatrix} \]

Quasi-optimal transfer matrices \( G^*_k \) based on the importance ranking index were calculated as follows

\[ G_1^* = \begin{pmatrix} 1/2 & 1 \\ 2/1 & 1 \end{pmatrix} \quad G_2^* = \begin{pmatrix} 1/2 & 1 \\ 2/1 & 1 \end{pmatrix} \quad G_3^* = \begin{pmatrix} 1/2 & 1 \\ 2/1 & 1 \end{pmatrix} \]

\[ G_4^* = \begin{pmatrix} 1/2 & 1 \\ 2/1 & 1 \end{pmatrix} \]

The weight vector of the L8 limestone aquifer and the L2 limestone-Ordovician limestone aquifer was calculated by the sum-product method as follows

\[ W_1^* = (0.586, 0.414) \]

The weight vector of the L8 limestone aquifer and the L2 limestone-Ordovician limestone aquifer was calculated by the square root method as follows

\[ W_2^* = (0.667, 0.333) \]
The weight vector of the L8 limestone aquifer and the L2 limestone–Ordovician limestone aquifer was calculated by the series binary comparison method as follows

\[ W^* = (0.6, 0.4)(0.667, 0.333) \]

Weight decision-making was conducted (as shown below) by the geometric averaging operator.

\[ W^* = \left( \prod_{i=1}^{3} W_i^* \right)^{1/3} = (0.618, 0.382) \]

The ordered binary comparison quantization method was coupled with the work breakdown structure and the RBS theory to determine the weight matrix of indicators, as shown in Table 8.

Weights of evaluation indicators for the risk assessment of water inrush from the L8 limestone aquifer and the L2 limestone–Ordovician limestone aquifer during No. 21 coal seam mining in Guhanshan minefield are shown in Tables 9 and 10.

Gray Assessment of Water Inrush Risk Based on the Center-Point Triangular Whitenization Weight Function. Assuming that the number of gray classifications is \( s \), the number of evaluation indicators is \( m \), and the number of evaluation objects is \( n \), the sample observation of the evaluation object \((i)\) for the evaluation indicator \((j)\) is defined as \( x_{ij} \) (\( i = 1, 2, L, n \); \( j = 1, 2, ..., m \)), and the object \((i)\) is evaluated according to the sample observation \((x_{ij} (i = 1, 2, L, n; j = 1, 2, ..., m))\) of the evaluation object \((i)\) for the evaluation indicator \((j)\). When the gray classifications are divided, the point with the maximum value, which belongs to a certain gray classification, is called the center point. The concrete steps of the gray assessment model based on the center-point triangular whitenization weight function are as follows.

Step 1: The number of gray classifications is determined, and the center points \( \lambda_i \) of each gray classification are determined.

Step 2: The value range of the evaluation indicator \((j)\) is defined as \([\alpha_1, \alpha_{s+1}]\), and the whitenization weight function of the gray classification \( k \), whose center point is \( \lambda_k = (\alpha_k + \alpha_{k+1})/2 \), is defined as 1. The gray classifications 0 and \( s + 1 \) are added, and their corresponding center points are, respectively, determined as \( \lambda_0 \) and \( \lambda_{s+1} \), obtaining a new sequence of center points \( \lambda_0, \lambda_1, \lambda_2, ..., \lambda_{s+1} \). The center-point triangular whitenization weight function \( f^k_j(x) \) of the evaluation indicator \((j)\) for the gray classification \( k \) is obtained by connecting the center point \( \lambda_{k+1} \) with the center points of gray classifications \( k - 1 \) and \( k + 1 \). The sketch map of the center-point triangular whitenization weight function is shown in Figure 19.

The sample observation of the evaluation indicator \((j)\) is defined as \( x \), and the membership \( f^k_j(x) \) of the sample observation \( x \) belonging to gray classification \( k(k = 1, 2, ..., s) \) is calculated using the following formula

\[ f^k_j(x) = \begin{cases} 0, & x \notin [\lambda_{k-1}, \lambda_k] \\ \frac{x - \lambda_{k-1}}{\lambda_k - \lambda_{k-1}}, & x \in [\lambda_{k-1}, \lambda_k] \\ \frac{\lambda_{k+1} - x}{\lambda_{k+1} - \lambda_k}, & x \in [\lambda_k, \lambda_{k+1}] \end{cases} \]

Step 3: Comprehensive convergence coefficient \( \sigma^k_i \) of the evaluation object \((i)\) for gray classification \( k \) is calculated using the following formula

\[ \sigma^k_i = \sum_{j=1}^{m} f^k_j(x_{ij}) \eta_j \]

where \( f^k_j(x_{ij}) \) is the whitenization weight function of the evaluation indicator \((j)\) belonging to gray classification \( k \). \( \eta_j \) is the weight of the evaluation indicator \((j)\).

Step 4: Based on the formula \( \max \{ \sigma^k_i \} = \sigma^k_{1s} \), the classification the evaluation object \((i)\) belongs to is judged. If several objects belong to the same gray classification, the evaluation objects are ranked according to the comprehensive convergence coefficient.

Determination of Center Points. In this paper, four gray classifications are selected to represent “low risk”, “medium risk”, “high risk”, and “extremely high risk”. Combined with expert opinions, the center points of each gray classification are determined (Table 11).

Extension of Evaluation Indicators. Combined with the actual situation of the study area, the evaluation indicators are extended. Table 12 shows the extension values and actual values of each indicator. The 15031 working face is selected as an evaluation objective (Figure 20).

Whitenization Convergence Coefficients. \( \lambda^k_0 \) is calculated using the formula \( \lambda^k_0 = \frac{1}{k} (x_{ij} + x_{ij}^{-1}) \), and then \( \lambda^k_0 \) is substituted into the formula of membership, obtaining the whitenization convergence coefficients of evaluation indicators (Table 13).

**DISCUSSION AND CONCLUSIONS**

Discussion. The comprehensive convergence coefficients of the risk of water inrush from the L8 limestone aquifer and the L2 limestone–Ordovician limestone aquifer are shown in Table 14.

![Figure 21](https://doi.org/10.1021/acsomega.0c05853)
It can be seen from Table 14 that under the mining conditions of high pressure and high stress, the risk of water inrush from the broken floor is medium when mining the No. 21 coal seam in the 15031 working face. In terms of the water inrush risk for the L6 limestone aquifer, the 15031 working face poses medium risk as a whole, but the areas of high risk and extremely high risk account for a large section; therefore, there is a trend of transition to high risk and extremely high risk. In terms of the water inrush risk for the L2 limestone—Ordovician limestone aquifer, the 15031 working face also belongs to medium risk, which mainly exists in the areas with serious damage of the floor rock mass and the complex structure.

The above analysis shows that the risk of water inrush from the L6 limestone aquifer is higher when mining the No. 21 coal seam of Shaxi Formation in 15031 working face, which is consistent with the actual mining situation and the serious damage of the floor rock mass and the heaving floor under high pressure and high stress in Guhanshan minefield. It shows that the results of the gray assessment on the risk of water inrush from the broken floor based on the center-point triangular whitenization weight function are better.

Guhanshan minefield is divided into several small units with grids of 100 × 100, and the risk of water inrush from the No. 21 coal seam floor is assessed and predicted. The results are shown in Figures 21 and 22. According to the mine data on water inrush over the years, the water inrush sites basically locate in the areas with medium risk, which can better reflect the rationality of the evaluation results. However, special attention should be paid to the water inrush accidents caused by faults, which connect the L6 limestone aquifer with the L2 limestone—Ordovician limestone aquifer or the water flowing fractured zone.

**CONCLUSIONS**

(1) Taking the mining of the No. 21 coal seam as an example, by studying the distribution characteristics of high pressure and high stress, we expound the mechanism of water inrush from the broken floor. Then, five main factors affecting water inrush from the broken floor are determined, including fault fractal dimensions, aquifer pressure, aquifer water-richness, destroyed floor depth, and effective aquiclude thickness; then, the weight vector of each index is calculated using the ordered binary comparison quantization method coupled with the work breakdown structure and the RBS theory, which ensures the effective evaluation of the relative importance of each index in the dynamic model.

(2) Based on the center-point triangular whitenization weight function, a risk assessment model of water inrush from the broken floor is established, which is in line with the mining conditions of high pressure and high stress. Then, the evolution trend of the risk of water inrush from the L6 limestone aquifer and the L2 limestone—Ordovician limestone aquifer is predicted when the No. 21 coal seam is continuously mined. The results show that the L6 limestone aquifer poses a great threat to the mining of the No. 21 coal seam in Guhanshan minefield, while the threat of the L2 limestone—Ordovician limestone aquifer to the mining of the No. 21 coal seam in Guhanshan minefield is mainly concentrated in areas with the developed fracture structure.

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