Method for Evaluating Fault Hydraulic Conductive Property and Its Application in Shandong, China

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ABSTRACT: Coal remains the largest contributor to the energy structure of China. However, coal production is frequently threatened by groundwater inrush accidents caused by hydraulically conductive faults. Despite the threat of such accidents, research on methods for evaluating fault hydraulic conductive property without hydraulic tests has seldom been conducted. Many faults exist in coal mines in Shandong, China. However, due to economic and technical limitations, hydrological tests are rarely performed and can be performed on only a few faults. The hydraulic conductive property of many faults is unknown, which has prevented serious groundwater inrush accidents and casualties from being avoided. Using accessible geological exploration data, we propose a method for evaluating fault hydraulic conductive property in the Jining coalfield, Shandong, China. Mudstone smearing, lithologic contact relations on the fault plane, geostress, water pressure, plastic deformation of mudstone, and the argillaceous content of the fault zone were selected as factors, and six quantitative indicators were proposed: the shale gouge ratio (SGR), lithologic juxtaposition diagram (LJD), fault closure coefficient (FCC), water pressure coefficient (WPC), mudstone deformation coefficient (MDC), and shale smear factor (SSF). The fuzzy analytic hierarchy process (FAHP) was applied to calculate the weights and establish lateral and vertical hydraulic conductive property (L and V) evaluation models for faults. The fault hydraulic conductivities were then classified as weak, medium, or strong. The hydrochemical experiments and the limited number of exposed faults were used for validation. Hence, the evaluation models were considered effective at determining the hydraulic conductive property of faults in the Jining coalfield, China.

1. INTRODUCTION

Mine water inrush, as a serious accident threatening the safety of coal mining, has three necessary conditions: water sources, water inrush channels, and sufficient water yield, and faults are one of the main channels for water inrush accidents. Faults are structures widely distributed in the strata that affect the migration of fluids in the strata. Faults may be either barriers or channels for fluid flow depending on the internal structure of the fault. The internal structure of the fault changes the hydraulic conductive property of the primary rock mass, which may lead to an increase or decrease in the hydraulic conductive property of the fault, and the hydraulic conductive property of the fault is the factor affecting the fault as a fluid migration channel. According to the latest statistics on mine water inrush accidents in China over the last 50 years, almost 80% of these incidents were related to hydraulically conductive faults. In recent years, due to improvements in safety awareness, the frequency of water inrush accidents in coal mines has been decreasing, but the percentage of water inrush accidents caused by hydraulically conductive faults has been increasing rapidly. Therefore, determining the fault hydraulic conductive property is of great significance to the safety of mining.

Over the past few decades, geologists in different fields have tried different methods to study the effect of faults on fluid flow, including laboratory tests such as hydrochemical analysis and core testing and field tests such as pumping tests and borehole geophysical analysis. These studies have shown that the hydraulic conductive property of faults may depend on field-scale geological features, groundwater conditions, fillings/granular rocks within the fault zone, rock mineralogy, and other influential aspects. These studies have enriched the theory of fault hydraulic conductive property. However, most of the previous research methods cost considerable time and money. In addition, the complex internal structure of faults may lead to anisotropy of fault hydraulic conductive property. Previous research methods could only obtain the local hydraulic conductive property characteristics of one or several adjacent faults and could not determine the overall
hydraulic conductive property of faults. Coal mines with a large number of faults are very common in China; however, only a few faults in a coal mine can be hydrogeologically tested for economic reasons; thus, a rapid and economical method for evaluating the hydraulic conductive property that can be applied to multiple faults simultaneously is needed. A fast and economical method to evaluate the conductivity of faults in coal mines is urgently needed. Therefore, exploring a hydraulic conductive property evaluation method for multiple faults that does not require laboratory or field tests is of great significance.

In the present study, the theory of fault sealing is used for reference in the evaluation of fault hydraulic conductive property. The evaluation of fault sealing is a common method in petroleum exploration; fault sealing describes a fault’s ability...
to prevent fluid flow; thus, it has reference significance to the evaluation of fault hydraulic conductive property. Based on the analysis of research results on fault hydraulic conductive property and fault sealing, six factors influencing the fault hydraulic conductive property were selected for evaluation in this study: the occurrence of mudstone smearing, lithologic contact relations at the fault plane, the geostress state, water pressure conditions, plastic deformation of the mudstone, and argillaceous content of the fault zone. The shale smear factor (SSF), permeable strata docking ratio (PDR), fault closure coefficient (FCC), water pressure coefficient (WPC), mudstone deformation coefficient (MDC), and shale gouge ratio (SGR) were used to evaluate the fault hydraulic conductive property. Two mathematical models for evaluating fault hydraulic conductive property were established and applied to 21 faults in the Jining no. 2 coal mine (JCM), and the results were verified and found to be very acceptable. The aims of this study were to propose a hydraulic conductive property evaluation method that is applicable to multiple faults without the need for laboratory or field tests to prevent coal mine water disasters and to provide new findings that can enhance our understanding of the hydrogeology of mines.

2. STUDY AREA AND GEOLOGIC AND HYDROGEOLOGICAL SETTINGS

2.1. Study Area. The area containing the JCM, which is the focus of the current study, lies in Jining, Shandong Province, China (Figure 3). The site lies between 35°19′03″−35°25′28″N, 116°32′35″−116°41′02″E and covers an area of approximately 87.1 km². The mean annual rainfall in the area is 701.21 mm, and the mean annual temperature is 14.2 °C (Table 1). Few seasonal streams form in the coalfield. Generally, the area hosts a faulted and folded monocline with a north–south strike and an eastward dip. The major of 4 Mt/a. Mining activities in the JCM have been focused on coal seam no. 3, which is thick, extensive, and of high quality. The coal deposit is formed in the Permian. A recent investigation shows that the Ordovician limestone aquifer has a large amount of water flow, and although it is located a certain distance from the mined coal seam, hydraulically conductive faults may act as water gushing passageways, allowing water from the Ordovician limestone aquifer into the mine, which thereby increases water inflow into the mine and can cause water inrush accidents. Therefore, analyzing the hydraulic conductive property of faults in this mining area has become necessary.

2.2. Geology. The JCM is located in a typical North China coalfield of the Permo-Carboniferous age. The coal-bearing deposits are located in the Benxi Formation (Fm), Taiyuan Fm, Shanxi Fm, and Shihezi Fm. The strata at the base of the coal deposits are Ordovician in age and mainly comprise thick limestone and thin mudstone, both of which are gray to dark gray. The third coal seam is mined and belongs to the Shanxi Fm, as shown in Figure 2.

The JCM is located in the Jining coalfield, Shandong Province, and is a very large mine with a designed production

Table 1. General Information on the Study Area

| geographic information | study area |
|------------------------|------------|
| topography             | diluvial plains of the Yellow River and a flat terrain |
| location               | 35°19′03″−35°25′28″N, 116°32′35″−116°41′02″E |
| area                   | 87.1067 km² |
| elevation range        | 37−33 m    |
| mean rainfall          | 701.21 mm  |
| mean evaporation       | 1758.75 mm |
| mean temperature       | 14.2 °C    |
| rivers                 | seasonal streams |
faults are oriented NNW-SSE, whereas others are oriented ENE-WSW and NNE-SSW (Figure 4). A total of 2768 faults have been identified, including 2666 with a fault throw of less than 10 m, 78 with a fault throw of 10−30 m, and 24 with a fault throw of more than 30 m.

2.3. Hydrogeology. The lithology of the main aquifers is dominated by the Ordovician limestone and sandstone within the Permo-Carboniferous deposits. The main aquifers include clay beds in the Jurassic strata and mudstone and siltstone in the Permo-Carboniferous strata (Figure 2). The main water-filled aquifer on the mine floor is an Ordovician aquifer composed of limestone, which is considered a karst aquifer under the condition of confined flow. This aquifer is a typical karst confined aquifer, with an average thickness of 742 m and a depth of 866.7 m below the surface. The water yield per unit of drawdown varies from 1.1178 L/s/m to 3.1502 L/s/m based on data collected during three drawdowns of a single-well pumping test in the limestone aquifers at wells no. 4-1 and no. 7-11. The initial water levels ranged between 34.97 and 35.12 m and were calculated using information from these two boreholes. The data showed that the aquifer had a high water yield. The main Ordovician limestone aquifer on the mine floor is widely distributed, very thick, and has a high local water yield. The water is under high pressure; thus, this aquifer poses a significant threat to the mine. 28

3. DATA

3.1. Identified Factors and Quantitative Measures. The hydraulic conductive property of faults is very complicated, and it is restricted by many factors. Based on the theoretical relationship between the sealing and hydraulic conductive property of faults and current research on hydraulic conductive property and fault sealing, we divided hydraulic conductive property into two types: the vertical hydraulic conductive property and lateral hydraulic conductive property (Figure 5). The vertical hydraulic conductive property of faults refers to the ability of water at different elevations in a fault zone to migrate along a fault along the tangent direction of the fault plane (Figure 5a). The lateral hydraulic conductive property refers to the ability of water from one plate of a fault to move across the fault plane along the normal direction of the fault to another plate at the same elevation (Figure 5b). Six factors influencing the fault hydraulic conductive property were selected: the occurrence of mud-

![Figure 4](https://example.com/faults_map.jpg)

Figure 4. Sketch map of the structural geology of the JCM.
3.2. Factors.

3.2.1. Mudstone Smearing. Studies on fault sealing properties have demonstrated that a mudstone smear is the result of the formation of a mudstone layer along the fault plane under compressive stress during the dragging of rock strata, including mudstone induced by fault activity. A large number of field observations show that mudstone smears are common along both normal and reverse faults. The poor permeability of such mudstone layers along fault planes enhances the lateral sealing property of faults, which can prevent water migration along the fault plane, weakening the lateral hydraulic conductive property of the fault. Therefore, mudstone smearing was selected as a factor.

3.2.2. Lithologic Contact Relations along the Fault Plane. A model of sandstone and mudstone contact has been proposed for oil and gas reservoirs (Figure 6). According to this model, when permeable strata on both sides of the fault are in contact, the fluid can move through the fault plane to the other side of the fault, allowing lateral fluid flow. In contrast, when impermeable strata are in contact with permeable or impermeable strata, the fluid flow between the two sides of the fault is difficult to generate, and the lateral hydraulic conductive property of the fault is weak.

3.2.3. Geostress. The study of oil and gas exploration shows a strong relationship between geostress and fault sealing properties. Geostress affects the normal and tangential stresses acting on the fault plane. The compressive stress of the fault plane leads to a high closure degree of the fault plane, which enhances vertical and lateral fault sealing and weakens the vertical and lateral hydraulic conductive properties. Therefore, geostress was regarded as a factor that could influence fault vertical and lateral hydraulic conductive properties.

3.2.4. Water Pressure of the Aquifer. With the goal of ensuring the safety of coal mining, some Chinese scholars have studied the water conductivity of coal-measure faults. Their results show that under the influence of high water pressure, fractures along the fault plane tend to open, and water from the aquifer can migrate along the fault zone, leading to vertical hydraulic conductive property along the fault. Therefore, water pressure is another important factor affecting the vertical hydraulic conductive property of faults.

3.2.5. Plastic Deformation of the Mudstone. The theory of rock deformation suggests that plastic deformation of mudstone occurs when the pressure reaches the elastic limit of the rock. Some studies have shown that in a compressive fault when the pressure does not exceed the plastic deformation limit of mudstone and the fault plane is closed under pressure, the mudstone is undeformed, rock voids are not blocked by the deformed mudstone, and the rock in the fault zone maintains its original permeability and sealing properties. However, when the pressure exceeds the plastic deformation limit of the mudstone, the voids in the rock of the fault zone become filled by deformed mudstone, which reduces the permeability of the fault zone and prevents the migration of the fluid. Therefore, we chose this factor as a factor that could influence the lateral and vertical hydraulic conductive properties of a fault.

3.2.6. Argillaceous Content in the Fault Zone. A study of 34 faults in the Liaohe Oilfield revealed that the higher the ratio of sandstone to mudstone in the fault zone, the poorer the fault sealing property. We conclude from this result that when the material in the fault zone mainly comprises sandstone particles, the fault sealing property is poor, and water can easily migrate; therefore, in this study, the argillaceous content in the fault zone is regarded as one of the factors influencing the hydraulic conductive property.

3.3. Quantitative Analysis of the Factors. Quantitative analysis can express some fuzzy factors with specific data for analysis and comparison. The factors influencing fault hydraulic conductive property are unclear; thus, the use of appropriate quantification methods to evaluate fault hydraulic conductive property is important. Six metrics were selected to evaluate fault hydraulic conductive property: the SGR, LJD, FCC, WPC, MDC, and SSF. 21 faults with a great influence on production were selected for evaluation, and the basic parameters are shown in Table 2.

3.3.1. SGR. The SGR was proposed to predict the argillaceous content in fault zones and has been widely used to analyze fault sealing. Field experiments show that the argillaceous content in fault zones has a significant positive correlation with the SGR, thus, in this paper, the SGR was used to measure the argillaceous content in the fault zones. The specific principle of the SGR is shown in Figure 7. The formation lithology and thickness through the fault were obtained according to the borehole core data, and the SGR ratio was calculated according to the formula in Figure 7. This
argillaceous layers and is widely used in the evaluation of lateral sealing with respect to oil and gas. The SSF were calculated and are shown in Table 3. The fault SGR was often used to evaluate the lateral hydraulic conductive property of faults, and its calculation formula is shown in Figure 10. A previous investigation has shown that the threshold value of the SSF is generally between 5 and 8, and that the lower the SSF value, the higher the development degree of the argillaceous layer along the fault plane, resulting in stronger lateral sealing and weaker lateral hydraulic conductive property. The SSF values of the studied faults are shown in Table 4. All were less than five, with 86% of them being less than three, which indicated that the argillaceous layers on the fault planes of all of the studied faults were well developed and weakened the lateral hydraulic conductive property of the faults.

Table 3. SGR Values of the Studied Faults

| fault | SGR | fault | SGR |
|-------|-----|-------|-----|
| F24   | 0.74| F48-1 | 0.80|
| F14   | 0.78| F9F   | 0.95|
| F25   | 0.64| F205  | 0.85|
| F287  | 0.89| F222  | 0.85|
| F137  | 0.89| F223  | 0.82|
| 9F1   | 0.81| 13F19 | 0.48|
| F220  | 0.65| 13F13 | 0.82|
| F224  | 0.49| 13F11 | 0.76|
| F51   | 0.60| F2    | 0.29|
| F269  | 0.56| F1    | 0.31|
| F48-2 | 0.72|       |     |

Figure 7. Schematic diagram of SGR and SSF.

ratio can be intuitively interpreted as the ratio of the mudstone formation thickness to the total formation thickness within a range of the vertical fault distance from a point in the fault movement direction.

The average SGR values of the 21 faults in the study area were calculated and are shown in Table 3. The fault SGR values were found to be between 0.29 and 0.95, with 81% being above 0.5 and 71% being above 0.7, indicating that the studied faults have high argillaceous contents.

3.3.2. SSF. During the fault formation period, the shale and mudstone in the footwall and hanging wall tend to maintain their original state but are dragged along the fault plane. When shale or mudstone with high plasticity is pulled into the developing fault zone, a thin argillaceous layer forms along the fault plane and its degree of development directly affects the lateral sealing of the fault with respect to oil and gas. The SSF is a common metric used to measure the development of argillaceous layers and is widely used in the evaluation of lateral sealing. In this paper, the SSF is used to evaluate lateral hydraulic conductive property of faults, and its calculation formula is shown in Figure 10. A previous investigation has shown that the threshold value of the SSF is generally between 5 and 8, and that the lower the SSF value, the higher the development degree of the argillaceous layer along the fault plane, resulting in stronger lateral sealing and weaker lateral hydraulic conductive property.

3.3.3. LJD. The LJD can intuitively reflect the lithologic contact relations between the two walls of a fault plane and is often used to evaluate lateral sealing properties of faults in oil and gas exploration. The LJD method was used in this paper to calculate the contact probability of permeable strata on the fault plane. The LJD process involves drawing a map of the permeable strata in the footwall and hanging wall of the fault (Figure 8a,b) and then superimposing the two maps to obtain the LJD (Figure 8c).

The distribution of contacts between permeable strata on the fault plane can be intuitively obtained from an LJD, as shown in Figure 13c. The PDR is defined as the contact probability of permeable strata on the fault plane, and it is calculated as the ratio of the docking zone to the total study area of the fault plane. According to a previous analysis, the PDR is positively correlated with the lateral hydraulic conductive property of a fault. The LJDs of the 21 faults were drawn, and the PDRs were calculated (Table 5). The PDR was between 2.68 and 57.74, with an average of 17.28. Overall, 95.2% of these values were less than 40, and 67% were less than 20, revealing substantial variation. The values of a few faults were high (>50).

3.3.4. FCC. The degree of fault closure has been quantitatively characterized and found to be controlled by the normal stress acting on the fault plane, and it has been used to evaluate vertical closure. Some studies have suggested that when a fault plane is under compressive stress, the fault tends to close, whereas when the fault plane is under tensile stress, the fault opens. The consensus of these studies is that the degree of fault closure is controlled by the normal stress on the fault plane. Based on this observation, we considered the normal stress on the fault plane (σ) as the FCC. The normal stress of the fault plane was calculated as follows. As shown in Figure 9, a three-dimensional coordinate system was established for the fault plane to facilitate stress...
analysis. The maximum horizontal principal stress direction ($\sigma_H$) was the positive X-axis direction, the minimum horizontal principal stress direction ($\sigma_h$) was the positive Y-axis direction, and the vertical principal stress direction ($\sigma_V$) was the positive Z-axis direction. The data were determined from the borehole stress relief measured near the coal seam. To facilitate this type of analysis, the following conditions should all be met: the fault strike and dip angle are known, the influences of lithology and the fault zone are not taken into account, and the material properties of the fault zone are uniform. The overall process involves the calculation of the normal stress and shear stress generated by $\sigma_H$, $\sigma_h$, and $\sigma_V$ acting on the fault plane and then the determination of the normal stress ($\sigma$) acting on the fault plane by superimposing the three calculated shear stresses and three normal stresses based on the theory of stress superposition.

The horizontal principal stress ($\sigma_{H}$) is taken as an example to illustrate the calculation process. Suppose the area of the fault plane is $A$, the projected area of the fault plane on the $yz$ plane is $A'$, and $S$ is the combined stress of $\sigma_H$ acting on the fault plane. According to the equilibrium conditions, the force exerted by $\sigma_H$ along the X-axis on the fault plane should be the same as the force exerted on the projection plane of the fault plane

$$AS = A'\sigma_H$$  \hspace{1cm} (1)

The combined stress $S$ is calculated according to the geometric relationship in Figure 9

$$S = \sigma_H\cos \theta_H$$  \hspace{1cm} (2)

$S$ can be decomposed into the normal stress $\sigma_{SH}$

$$\sigma_{SH} = S \cos \theta_H = \sigma_H \cos^2 \theta_H$$  \hspace{1cm} (3)

In the same way, the normal stresses $\sigma_{Sh}$ and $\sigma_{SV}$ generated by $\sigma_h$ and $\sigma_V$ on the fault plane, respectively, can be obtained

$$\begin{cases} \sigma_{Sh} = S \cos \theta_h = \sigma_h \cos^2 \theta_h \\ \sigma_{SV} = S \cos \theta_v = \sigma_v \cos^2 \theta_v \end{cases}$$  \hspace{1cm} (4)
According to stress superposition theory, the combined normal stress can be obtained

\[ \sigma = \sigma_{SH} + \sigma_{Sh} + \sigma_{SV} = \sigma_{H} \cos^2 \theta_{H} + \sigma_{h} \cos^2 \theta_{h} + \sigma_{v} \cos^2 \theta_{v} \]  

(5)

According to the in situ stress test in the study area, the value of \( \sigma_{H} \) and the azimuth angle are 24.45 MPa and 90.1°, respectively, and the value of \( \sigma_{h} \) and the azimuth angle are 2.24 MPa and 178.8°, respectively. \( \sigma_{v} \) is calculated by the weight of overlying strata of the coal seam floor, and the unit weight of strata is 0.0027 kg/cm³. The calculation results are shown in Table 6. The FCC values are between 2.39 and 18.99, with an average of 14. Among them, 86% are greater than 10, and 9% are less than five. Additionally, all of the fault planes are under compressive stress.

3.3.5. MDC. The theory of rock deformation suggests that plastic deformation of mudstone occurs when the stress in the mudstone reaches the elastic limit of the rock. Under high fault pressure, voids in the rock mass in the fault zone become filled by deformed mudstone, which reduces the permeability of the rock mass and results in poor hydraulic conductive property along the fault. For quantitative evaluation, the MDC, which is defined as the ratio of the normal stress of the fault plane to the elastic limit of the mudstone, was selected. The elastic limit of the mudstone was determined based on core mechanical tests of boreholes near the fault zone.

When the MDC is higher than 1, the mudstone deforms and fills the rock mass voids, resulting in reduced permeability of the rock mass in the fault zone and poor hydraulic conductive property in the vertical direction along the fault. The larger the MDC value, the higher the degree of mudstone deformation and the worse the hydraulic conductive property. The MDC values of the 21 faults were calculated and found to range between 1 and 2, with 90% being greater than 1, which showed that the mudstone had deformed along the studied faults (Table 7).

3.3.6. WPC. Water pressure is considered an important factor affecting the vertical conductivity of faults. Laboratory simulation experiments were used to explain the promotional effect of high water pressure on conductivity under low fault pressure. The authors of these studies agreed that the water pressure cannot be used to directly estimate hydraulic conductive property and that it needs to be considered together with the fault pressure to evaluate vertical hydraulic conductive property. Based on previous studies, in this study, the WPC, defined as the ratio of the water head pressure of the Ordovician limestone aquifer in the coal seam floor (\(P\)) to the normal stress on the fault plane (\(\sigma\)), was selected. \(P\) is calculated with eq 6

\[ P = (H - X + M) \times 0.01 \]  

(6)

where \(P\) is the head pressure at the floor of the coal seam (MPa); \(H\) is the height of the water level of the aquifer (m),
Figure 11. Hierarchy structure of fault hydraulic conductive property evaluation.

Figure 12. Frequency diagrams of \( L \) and \( V \).

Figure 13. Piper diagram indicating hydrochemical characteristics.
and according to the data measured in the study area, the value is +5.84 m; \( X \) is the height of the coal seam floor at the fault (m); and \( M \) is the distance between the floor and the aquifer (m).

A positive correlation exists between the WPC and vertical hydraulic conductive property. When the WPC is less than 1, the water pressure cannot break through the sealing action of the normal stress of the fault, resulting in poor vertical hydraulic conductive property and little fluid migration. When the WPC is greater than or equal to 1, the fault tends to prop open under the influence of the high fluid pressure, increasing the hydraulic conductive property. The calculated data are shown in Table 8.

| Table 5. PDR Values of the Studied Faults |
|-----------------|-----------------|
| fault | PDR (%) | fault | PDR (%) |
| F24 | 13.51 | F48-1 | 6.96 |
| F14 | 5.12 | F9F | 4.42 |
| F25 | 12.78 | F205 | 21.84 |
| F287 | 12.08 | F222 | 2.68 |
| F137 | 11.96 | F223 | 9.20 |
| 9F1 | 12.81 | 13F19 | 12.68 |
| F220 | 19.34 | 13F13 | 10.79 |
| F224 | 34.89 | 13F11 | 25.83 |
| F51 | 23.71 | F2 | 33.72 |
| F269 | 24.34 | F1 | 57.74 |
| F48-2 | 6.40 | |

Table 6. FCC Values of the Studied Faults

| fault | FCC (MPa) | fault | FCC (MPa) |
|-----------------|-----------------|
| F24 | 12.11 | F48-1 | 10.93 |
| F14 | 18.47 | F9F | 13.91 |
| F25 | 11.64 | F205 | 9.00 |
| F287 | 16.56 | F222 | 14.31 |
| F137 | 18.99 | F223 | 13.75 |
| 9F1 | 17.04 | 13F19 | 17.08 |
| F220 | 15.38 | 13F13 | 18.35 |
| F224 | 18.71 | 13F11 | 3.71 |
| F51 | 13.88 | F2 | 18.88 |
| F269 | 2.39 | F1 | 18.35 |
| F48-2 | 10.91 | |

Table 7. FCC Values of the Studied Faults

| fault | MDC | fault | MDC |
|-----------------|-----------------|
| F24 | 5.82 | F48-1 | 4.54 |
| F14 | 5.79 | F9F | 3.57 |
| F25 | 2.78 | F205 | 4.1 |
| F287 | 5.07 | F222 | 4.33 |
| F137 | 1.87 | F223 | 2.02 |
| 9F1 | 3.32 | 13F19 | 3.85 |
| F220 | 5.68 | 13F13 | 2.2 |
| F224 | 4.11 | 13F11 | 2.32 |
| F51 | 4.67 | F2 | 5.82 |
| F269 | 0.37 | F1 | 4.06 |
| F48-2 | 4.81 | |

Table 8. WPC Values of the Studied Faults

| fault | P (MPa) | WPC | fault | P (MPa) | WPC |
|-----------------|-----------------|-----------------|
| F24 | 5.56 | 0.46 | F48-1 | 8.06 | 0.74 |
| F14 | 6.06 | 0.33 | F9F | 7.26 | 0.52 |
| F25 | 6.06 | 0.52 | F205 | 7.06 | 0.78 |
| F287 | 5.26 | 0.32 | F222 | 7.06 | 0.49 |
| F137 | 6.46 | 0.34 | F223 | 6.86 | 0.50 |
| 9F1 | 7.56 | 0.44 | 13F19 | 7.86 | 0.46 |
| F220 | 7.76 | 0.50 | 13F13 | 8.36 | 0.46 |
| F224 | 6.76 | 0.36 | 13F11 | 8.86 | 2.39 |
| F51 | 6.86 | 0.49 | F2 | 6.96 | 0.37 |
| F269 | 7.36 | 3.08 | F1 | 7.16 | 0.39 |
| F48-2 | 7.81 | 0.72 | |

and according to the data measured in the study area, the value is +5.84 m; \( X \) is the height of the coal seam floor at the fault (m); and \( M \) is the distance between the floor and the aquifer (m).

A positive correlation exists between the WPC and vertical hydraulic conductive property. When the WPC is less than 1, the water pressure cannot break through the sealing action of the normal stress of the fault, resulting in poor vertical hydraulic conductive property and little fluid migration. When the WPC is greater than or equal to 1, the fault tends to prop open under the influence of the high fluid pressure, increasing the hydraulic conductive property. The calculated data are shown in Table 8.

### 4. METHODOLOGY

4.1. Procedures. The evaluation of fault hydraulic conductive property consisted of four main steps: (1) selecting the factors that control fault hydraulic conductive property and

and collecting geological data, (2) proposing and performing quantitative evaluation methods, (3) normalizing the data and building the index model, and (4) describing and validating the results. The process is shown in Figure 10.

4.2. Data Processing. To combine all of the available depth, thickness, geologic, tectonic, and lithological data into a unified model and account for the multiple scales of magnitude of the various parameters, the following normalization was employed (eq 7)

\[
    x' = \frac{x - \min\{x\}}{\max\{x\} - \min\{x\}}
\]

where \( x \) is the original value of a parameter, and \( \max\{x\} \) and \( \min\{x\} \) are the original maximum and minimum values, respectively. The negative correlation factors were calculated by \( \{1 - x'\} \). The data following normalization and negative correlation processing are shown in Table 9.

4.3. Determining Factor Weights. Obtaining the weights of the factors integrated during fault hydraulic conductive property evaluation is critical. In this study, we applied the fuzzy analytic hierarchy process (FAHP) to determine the

Table 9. Processed Data

| fault | PDR | SSF | MDC | SGR | FCC | WPC |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| F24 | 0.2 | 0.77 | 0.00 | 0.32 | 0.41 | 0.05 |
| F14 | 0.04 | 0.81 | 0.01 | 0.26 | 0.03 | 0 |
| F25 | 0.18 | 0.84 | 0.56 | 0.47 | 0.44 | 0.07 |
| F287 | 0.17 | 0.70 | 0.14 | 0.09 | 0.15 | 0 |
| F137 | 0.17 | 0.73 | 0.72 | 0.09 | 0 | 0.01 |
| 9F1 | 0.18 | 0.99 | 0.46 | 0.21 | 0.12 | 0.04 |
| F220 | 0.3 | 0.75 | 0.03 | 0.45 | 0.22 | 0.07 |
| F224 | 0.58 | 0.63 | 0.31 | 0.7 | 0.02 | 0.01 |
| F51 | 0.38 | 0.90 | 0.21 | 0.53 | 0.31 | 0.06 |
| F269 | 0.39 | 0.88 | 1.00 | 0.59 | 1 | 1 |
| F48-1 | 0.07 | 0.16 | 0.23 | 0.35 | 0.49 | 0.14 |
| F48-2 | 0.08 | 0.71 | 0.19 | 0.23 | 0.49 | 0.15 |
| 9F9 | 0.03 | 1.00 | 0.41 | 0 | 0.31 | 0.07 |
| F205 | 0.35 | 0.07 | 0.32 | 0.15 | 0.6 | 0.17 |
| F222 | 0 | 0.95 | 0.27 | 0.15 | 0.28 | 0.06 |
| F223 | 0.12 | 0.98 | 0.70 | 0.2 | 0.32 | 0.06 |
| 13F19 | 0.18 | 0.75 | 0.36 | 0.71 | 0.12 | 0.05 |
| 13F13 | 0.15 | 0.78 | 0.66 | 0.2 | 0.04 | 0.05 |
| 13F11 | 0.42 | 0.73 | 0.64 | 0.29 | 0.92 | 0.75 |
| F2 | 0.56 | 0.48 | 0.00 | 1 | 0.01 | 0.02 |
| F1 | 1 | 0.00 | 0.32 | 0.97 | 0.04 | 0.03 |
factor weights (Figure 11). The analytic hierarchy process (AHP) is widely used to calculate weights. However, determining the consistency of the judgment matrix is difficult due to its strong fuzziness and uncertainty. The FAHP was invented to solve this problem.37 The FAHP in this study consisted of four steps: (1) establishment of the fuzzy hierarchy model (Figure 14), (2) establishment of the fuzzy complementary judgment matrix \((A_1, A_2)\), (3) consistency-checking of the methods for the fuzzy reciprocal judgment matrix \((M_{1*}^f\) and \(M_{2*}^f\)), and (4) determination of the weight of each factor (Table 10). The steps of this FAHP have been described in detail in an earlier publication.38 The following are the detailed data of the weight calculations.

\[
A_1 = \begin{bmatrix}
0.5 & 0.6 & 0.9 & 0.9 \\
0.4 & 0.5 & 0.7 & 0.8 \\
0.1 & 0.3 & 0.5 & 0.6 \\
0.1 & 0.2 & 0.4 & 0.5
\end{bmatrix} \quad A_2 = \begin{bmatrix}
0.5 & 0.6 & 0.8 & 0.9 \\
0.4 & 0.5 & 0.8 & 0.8 \\
0.2 & 0.2 & 0.5 & 0.6 \\
0.1 & 0.1 & 0.4 & 0.5
\end{bmatrix}
\]

\[
W_{1*}^f = \begin{bmatrix}
0.5 & 0.545 & 0.611 & 0.640 \\
0.455 & 0.5 & 0.575 & 0.607 \\
0.389 & 0.425 & 0.5 & 0.533 \\
0.360 & 0.393 & 0.467 & 0.5
\end{bmatrix} \quad W_{2*}^f = \begin{bmatrix}
0.5 & 0.486 & 0.396 & 0.356 \\
0.514 & 0.5 & 0.591 & 0.632 \\
0.604 & 0.409 & 0.5 & 0.6 \\
0.644 & 0.368 & 0.457 & 0.5
\end{bmatrix}
\]

\[V = \sum_{i=1}^{n} W_f^i\]  

(9)

where \(L\) and \(V\) are the lateral and vertical hydraulic conductive property indexes, respectively; \(w_i\) and \(W_f^i\) are the weights of the factors; and \(fi\) and \(F_i\) are the influencing factors. Based on the use of the FAHP to determine the weight of each factor, the index models for evaluating the fault hydraulic conductive property are given by eqs 10 and 11.

\[L = 0.209SGR + 0.283SSF + 0.183MDC + 0.325PDR\]

(10)

\[V = 0.208SGR + 0.175MDC + 0.317WPC + 0.3FCC\]

(11)

5. RESULTS AND DISCUSSION

5.1. Results. After processing the basic evaluation data and establishing the evaluation model, the lateral and vertical hydraulic conductive property indexes \((L, V)\) of 21 faults in the study area were calculated (Table 11). L and V were classified as strong (>0.6 and >0.70), medium (0.5–0.6 and 0.35–0.70), and weak (<0.50 and <0.35) using the natural grading method (Figure 12).

Table 11. Evaluation Results

| fault | \(L\) | grade | \(V\) | grade |
|-------|------|------|------|------|
| F24   | 0.3498 | weak  | 0.2054 | weak  |
| F14   | 0.2976 | weak  | 0.0640 | weak  |
| F25   | 0.4965 | weak  | 0.3496 | weak  |
| F287  | 0.2973 | weak  | 0.0878 | weak  |
| F137  | 0.4133 | weak  | 0.1487 | weak  |
| F137  | 0.4133 | weak  | 0.1487 | weak  |
| F220  | 0.4085 | weak  | 0.1863 | weak  |
| F224  | 0.5705 | medium| 0.2097 | weak  |
| F51   | 0.5276 | medium| 0.2592 | weak  |
| F269  | 0.6821 | strong| 0.9147 | strong|
| F48-2 | 0.1842 | weak  | 0.3053 | weak  |
| F48-1 | 0.3089 | weak  | 0.2748 | weak  |
| F9F   | 0.3683 | weak  | 0.1874 | weak  |
| F205  | 0.2227 | weak  | 0.3203 | weak  |
| F222  | 0.3502 | weak  | 0.1821 | weak  |
| F223  | 0.4857 | weak  | 0.2786 | weak  |
| F220  | 0.4857 | weak  | 0.2786 | weak  |
| F222  | 0.4857 | weak  | 0.2786 | weak  |
| F220  | 0.4857 | weak  | 0.2786 | weak  |
| F222  | 0.4857 | weak  | 0.2786 | weak  |

5.2. Validating the Evaluation. Many faults occur in this area, and the hydraulic conductive property of these faults affects the hydraulic connection between aquifers. In addition, several faults were exposed due to continuous mine excavation during the course of this study. Water inflow is generally recognized to occur at sites where hydraulically conductive faults are exposed in coal mines.38 Therefore, the hydrochemical characteristics of different aquifers and the exposed faults were considered to be representative and reliable for evaluating the hydraulic conductive property of faults in this area. Validation was accomplished by comparing the hydor-
Table 12. Validation Using Exposed Faults

| Fault | Exposure Position | Fault Throw | Water Inflow | Evaluation Result | Comparison |
|-------|-------------------|-------------|--------------|-------------------|------------|
| F222  | no. 1103 working face | 25 m | no water | weak | agree |
|       | no. 1102 working face | 9.5 m | no water | weak | agree |
|       | no. 9308 ventilation tunnel | 8.2 m | no water | weak | agree |
|       | no. 9309 ventilation tunnel | 11.5 m | no water | weak | agree |
|       | conveyor belt tunnel of no. 9 mining area | 7.5 m | no water | weak | agree |
|       | ventilation tunnel of no. 10 mining area | 19 m | no water | weak | agree |
| 9F1   | no. 9311 ventilation tunnel | 15 m | no water | weak | agree |
|       | no. 2 conveyor belt tunnel of the south wing | 14 m | no water | weak | agree |
|       | ventilation tunnel of no. 10 mining area | 14 m | no water | weak | agree |
| F205  | connection tunnel of the south wing | 38 m | no water | weak | agree |
|       | auxiliary haulage tunnel of no. 11 mining area | 38 m | no water | weak | agree |
| F220  | main ventilation tunnel of the south wing | 16 m | no water | weak | agree |
| 13F19 | no. 2 conveyor belt tunnel of the south wing | 24 m | no water | weak | agree |
| F51   | ventilation tunnel of no. 10 mining area | 19 m | no water | medium lateral conductivity | disagree |
| 9F9   | track transportation tunnel of the south wing | 6 m | no water | weak | agree |

The chemical characteristics of Permian and Ordovician water with the water inflow at the fault exposure site. The total dissolved solid (TDS) values of the Permian coal mine groundwater range from 4328.4 to 7994.9 mg L\(^{-1}\), with an average of 5522.7 mg L\(^{-1}\); the TDS values of Ordovician water range from 3186.61 to 3825.95 mg L\(^{-1}\), with an average of 3496.5 mg L\(^{-1}\). The Permian TDS values are higher than those of the Ordovician water. Figure 13 illustrates the results of hydrochemical experiments conducted in the study area. The Permian and Ordovician water types are \(\text{SO}_4\)\(^{-}\), \(\text{Ca}\), \(\text{Na}\), and \(\text{HCO}_3\)\(^{-}\) respectively. The hydrochemical experimental data show that the hydraulic connection between the two aquifers is poor, which indicates that the overall hydraulic conductive property of faults in this area is weak. The experimental results are consistent with the evaluation.

The results of observations from 14 exposure sites along six faults agreed with the abovementioned verification, and only the results of F51 differed from the calculated results. Information on the exposed faults is provided in Table 12. Field photographs of the exposed sites of faults F220 and F222 are shown in Figure 14, showing a high argillaceous content and no water in the fault zone, and this phenomenon agrees with the results of this study.

5.3. DISCUSSION

To mitigate water disasters caused by faults in the JCM, the mechanisms of fault hydraulic conductive property and fault sealing were analyzed, and an evaluation method was proposed. The evaluation results showed weak hydraulic conductive property for most of the studied faults, with 71.4 and 90.5% of the faults having weak lateral and vertical conductivities, respectively. The faults with medium lateral conductivity were F224, F51, 13F11, F1, and F2; this level was due to their high PDR (23.71–53.74). F269 had a high PDR (24.34) and low SSF and MDC (1.5 and 0.37, respectively), resulting in a strong lateral hydraulic conductive property. The vertical hydraulic conductivities of 13F11 and F269 were medium and strong, respectively, due to their low FCC (3.71 and 2.39) and high WPC (3.08 and 2.39). Based on the results from 15 exposed sites on seven faults, the accuracy of the evaluation was determined to be 85.7%. The characteristics of fault F51 disagreed with the verification results, possibly because the nearby aquifer was temporarily drained due to the high-intensity mining over a large area near F51, resulting in the misleading appearance of weak conductivity.

Unlike this study, most relevant studies have focused on the permeability of fault zones. Laboratory experiments, in situ hydraulic tests, and numerical simulations have been widely used to study single large faults (with fault throws greater than 50 m), while small faults (with fault throws less than 50 m) have been ignored.\(^6\)–\(^8\) The reason for this difference is the limits imposed by economic conditions; not every fault can be tested for hydraulic conductive property. In fact, only a few large faults in coal mines can be tested, and the hydraulic conductive property of small faults remains unclear, which has led to the great threat of mine water inrush in coal mines. Coal mines with multiple small faults are common in eastern China. However, due to the lack of fault hydraulic conductive property evaluation methods, fault density is often used to assess the fault hydraulic conductive property to evaluate the risk of mine water inrush.\(^27\) Although this approach has been widely used, it may fail to predict some disasters. In the Tianzhuang coal mine, 30 km from the JCM, a water inrush accident occurred along a small hydraulically conductive fault in 2010, with a water inflow of 900 m\(^3\)/h, causing great economic loss. Similar to this paper, Wei et al. (2021) evaluated the conductivity of the F1 fault in the Nantun Coal Mine near the research area of this paper by collecting lithology and water pressure, calculating the pressure of the fault plane, and verifying it using geophysical data.\(^39\) This also shows that the method in this paper is effective.

The purpose of this study was to propose a reasonable fault hydraulic conductive property evaluation method. In some mining areas with many small faults, the method proposed in this paper can obtain the relative hydraulic conductive property of faults, which can be used to design prevention measures for faults with relatively high conductivity, such as drilling the faults in advance and using appropriate waterproof coal pillars to prevent fault-related water inrush disasters.

6. CONCLUSIONS

To prevent coal mine water inrush disasters, determining the hydraulic conductive property of faults is essential. However, analyzing fault hydraulic conductive property without hydraulic test data is challenging. Two evaluation methods of fault hydraulic conductive property were successfully applied...
to 21 faults in the JCM, Shandong Province, China, without using hydraulic test data. Six factors influencing fault hydraulic conductive property were selected: the occurrence of mudstone smearing, lithologic contact relations at the fault plane, the geostress state, water pressure conditions, plastic deformation of the mudstone, and argilaceous content of the fault zone. Based on the analysis of the fault hydraulic conductive property mechanism, six quantitative measures were selected to build the evaluation model. PDR, SSF, SGR, and MDC were selected as lateral hydraulic conductive property evaluation indexes, and WPC, FCC, SGR, and MDC were selected as vertical hydraulic conductive property evaluation indexes. The weights were determined by the FAHP, and lateral and vertical hydraulic conductive property evaluation models were established.

Based on the evaluation models, the hydraulic conductive property values of 21 faults in the JCM were evaluated. The lateral and vertical hydraulic conductivities were divided into three grades: weak, medium, and strong. The evaluation results were compared with the observations of water inflow from faults exposed during mining, and the evaluation models were largely in agreement with the field data, thereby supporting the applicability of this method.

The results of the study can be used in mine water disaster prevention and control. They can also be applied in other coal mines with multiple faults. The proposed model approach represents a new method for the study of coal mine hydrogeology.

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**REFERENCES**

(1) Choi, J.-H.; Edwards, P.; Ko, K.; Kim, Y.-S. Definition and classification of fault damage zones: A review and a new methodological approach. *Earth-Sci. Rev.* 2016, 152, 70–87.

(2) Bu, F.; Xu, T.; Wang, F.; Yang, Z.; Tian, H. Influence of highly permeable faults within a low-permeability and low-permeability reservoir on migration and storage of injected CO₂. *Geofluids* 2016, 16, 769–781.

(3) Cilona, A.; Aydin, A.; Johnson, N. M. Permeability of a fault zone crosscutting a sequence of sandstones and shales and its influence on hydraulic head distribution in the Chatsworth Formation, California, USA. *Hydrogeol. J.* 2015, 23, 405–419.

(4) Meng, L.; Fu, X.; Wang, Y.; Zhang, X.; Lü, Y.; Jiang, Y.; Yang, H. Internal structure and sealing properties of the volcanic fault zones in Xujiawei Fault Depression, Songliao Basin, China. *Petrol. Explor. Dev.* 2014, 41, 165–174.

(5) Roques, C.; Aquílnia, L.; Bour, O.; Maréchal, J.-C.; Dewandel, B.; Pauwels, H.; Labasque, T.; Vergnaud-ayraud, V.; Hochreutener, R. Groundwater sources and geochemical processes in a crystalline fault aquifer. *J. Hydrol.* 2014, 519, 3110–3128.

(6) Fisher, Q. J.; Haneef, J.; Grattoni, C. A.; Allsborn, S.; Lorinzi, P. Permeability of fault rocks in siliciclastic reservoirs: Recent advances. *Mar. Petrol. Geol.* 2018, 91, 29–42.

(7) Bense, V. F.; Gleeson, T.; Loveless, S. E.; Bour, O.; Scibek, J. Fault zone hydrogeology. *Earth-Sci. Rev.* 2013, 127, 171–192.

(8) Ballas, G.; Soliva, R.; Benedicto, A.; Sizun, J.-P. Control of tectonic setting and large-scale faults on the basin-scale distribution of deformation bands in porous sandstone (Provence, France). *Mar. Pet. Geol.* 2014, 55, 142–159.

(9) Brandenburg, J. P.; Alpak, F. O.; Solum, J. G.; Naruk, S. J. A kinematic trishear model to predict deformation bands in a fault-propagation fold, East Kaibab monocline, Utah. *AAPG Bull.* 2012, 96, 109–132.

(10) Balsamo, F.; Storti, F.; Salvini, F.; Silva, A. T.; Lima, C. C. Structural and petrophysical evolution of extensional fault zones in low-porosity, poorly lithified sandstones of the Barreiras Formation, NE Brazil. *J. Struct. Geol.* 2010, 32, 1806–1826.

(11) Tueckmantel, C.; Fisher, Q. J.; Grattoni, C. A.; Aplin, A. C. Single- and two-phase fluid flow properties of cataclastic fault rocks in porous sandstone. *Mar. Pet. Geol.* 2012, 29, 129–142.

(12) Zhu, B.; Wu, Q.; Yang, J.; Cui, T. Study of pore pressure change during mining and its application on water inrush prevention: a numerical simulation case in Zhaogezhuang coalmine, China. *Environ. Earth Sci.* 2014, 71, 2115–2132.

(13) Huang, Z.; Jiang, Z.; Qian, Z.; Cao, D. T. Analytical and experimental study of water seepage propagation behavior in the fault. *Acta Geodyn. Geomater.* 2014b, 11, 361–370.

(14) Zhang, R.; Jiang, Z.; Zhou, H.; Yang, C.; Xiao, S. Groundwater outbursts from faults above a confined aquifer in the coal mining. *Nat. Hazards* 2014, 71, 1861–1872.

(15) Ma, D.; Bai, H.; Chen, Z.; Pu, H. Effect of particle mixture on seepage properties of crushed mudstones. *Transp. Porous Media* 2015, 108, 257–277.

(16) Chen, Y.; Yu, B.; Zhang, K.; Zhang, M.; Xu, G.; Chen, Z. Permeability evolution and particle size distribution of saturated crushed sandstone under compression. *Geofluids* 2018, 2018, 1–12.

(17) Neuman, S. P. Trends, prospects and challenges in quantifying flow and transport through fractured rocks. *Hydrogeol. J.* 2005, 13, 124–147.
(18) Audouin, O.; Bodin, J. Analysis of slug-tests with high-frequency oscillations. *J. Hydrol.* 2007, 334, 282–289.
(19) Hamm, S.-Y.; Kim, M.; Cheong, J.-Y.; Kim, J.-Y.; Son, M.; Kim, T.-W. Relationship between hydraulic conductivity and fracture properties estimated from packer tests and borehole data in a fractured granite. *Eng. Geol.* 2007, 92, 73–87.
(20) Angulo, B.; Morales, T.; Uriarte, J. A.; Antiguedad, I. Hydraulic conductivity characterization of a karst recharge area using water injection tests and electrical resistivity logging. *Eng. Geol.* 2011, 117, 90–96.
(21) Quinn, P. M.; Cherry, J. A.; Parker, B. L. Quantification of non-Darcian flow observed during packer testing in fractured sedimentary rock. *Water Resour. Res.* 2011, 47, W09533.
(22) Quinn, P. M.; Parker, B. L.; Cherry, J. A. Using constant head step tests to determine hydraulic apertures in fractured rock. *J. Contam. Hydrol.* 2011b, 126, 85–99.
(23) Quinn, P. M.; Parker, B. L.; Cherry, J. A. Validation of non-darcian flow effects in slug tests conducted in fractured rock boreholes. *J. Hydrol.* 2013, 486, 505–518.
(24) Huang, Z.; Li, X.; Li, S.; Zhao, K.; Zhang, R. Investigation of the hydraulic properties of deep fractured rocks around underground excavations using high-pressure injection tests. *Eng. Geol.* 2018, 245, 180–191.
(25) Rutter, E. H.; Hackston, A. J.; Yeatman, E.; Brodie, K. H.; Mecklenburgh, J.; May, S. E. Reduction of friction on geological faults by weak-phase smearing. *J. Struct. Geol.* 2013, 51, 52–60.
(26) Li, L.; Li, W.; Shi, S.; Yang, Z.; He, J.; Chen, W.; Yang, Y.; Zhu, T.; Wang, Q. An Improved Potential Groundwater Yield Zonation Method for Sandstone Aquifers and Its Application in Ningxia, China. *Nat. Resour. Res.* 2022, 31, 849–865.
(27) Philipp, S. L.; Afşar, F.; Gudmundsson, A. Effects of mechanical layering on hydrofracture emplacement and fluid transport in reservoirs. *Front. Earth Sci.* 2013, 1, 4.
(28) Li, L.; Xie, D.; Wei, J.; Yin, H.; Li, G.; Man, X.; Zhang, W. Analysis and control of water inrush under high-pressure and complex karstic water-filling conditions. *Environ. Earth Sci.* 2020, 79, 493.
(29) Liu, Z.; Lyu, Y. F.; Fu, X. F.; He, X. Y. Quantitative research on lateral seal ability of faults in Beier depression. *J. Jilin Univ.* 2012, 42, 353–361.
(30) Lyu, Y.; Wang, W.; Hu, X.; Fu, G.; Shi, J.; Wang, C.; Liu, Z.; Jiang, W. Quantitative evaluation method of fault lateral sealing. *Petrol. Explor. Dev.* 2016, 43, 340–347.
(31) Wang, K.; Dai, J. A quantitative relationship between the crustal stress and fault sealing ability. *Acta Petrol. Sin.* 2012, 33, 74–81.
(32) Zhang, S. J. Study on permeability of typical faults in deep coal seams. *China Energy Environ. Protect.* 2020, 42, 61–67.
(33) Fu, X.; Yan, L.; Meng, L.; Liu, X. Deformation Mechanism and Vertical Sealing Capacity of Fault in the Mudstone Caprock. *J. Earth Sci.* 2019, 30, 367–375.
(34) Lyu, Y. F.; Li, G. H.; Wang, Y. W. Quantitative research method of fault lateral sealing. *Acta Petrol. Sin.* 1996, 17, 39–43.
(35) Yielding, G. Shale Gouge Ratio - calibration by geohistory. *Hydrocarbon Seal Quantification;* Norwegian Petroleum Society Special Publications; Elsevier, 2002; Vol. 11(02), pp 1–15.
(36) Li, L. N. Study on Prediction, Evaluation and Application of Faults Hydraulic Conductive Property. Dissertation, Shandong University of Science and Technology, Qingdao City, Shandong Province, China, 2020.
(37) Buckley, J. J. Fuzzy hierarchical analysis. *Fuzzy Set Syst.* 1985, 17, 233–247.
(38) Lu, Q.; Li, X.; Li, W.; Chen, W.; Li, L.; Liu, S. Risk Evaluation of Bed-Separation Water Inrush: A Case Study in the Yangliu Coal Mine, China. *Mine Water Environ.* 2018, 37, 288–299.
(39) Wei, J.; Niu, H.; Xie, D.; Yin, H.; Li, G.; Zhong, C.; Li, L.; Xu, Y. Water permeability evaluation of fault zone in underground coal mines. *Arabian J. Geosci.* 2021, 14, 525.