Evaluation of roadway water hazard level based on extension connection cloud model

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Abstract. Accurately assessment of water hazard level in coal mine can improve the water hazard prevention and control in coal mine and reduce the occurrence of water inrush disaster. Based on the theoretical and practical study of coal mine water disaster accidents, a water disaster assessment index system was established. The transformation between qualitative and quantitative indicators was realized by the matter-element extension theory and the cloud model, the state value of the index and the corresponding risk grade membership value were determined by the connection cloud model, and the method of game theory was used to value the comprehensive weight of evaluation index to reduce the randomness and subjectivity in the determination of weight. Based on the principle of distance similarity, the evolution trend of risk can was estimated to strengthen the early warning of trend risk. The application in Feicheng mining area showed that the extension connection cloud model evaluation is appropriate to the evaluation of coal mine water hazard, and the quantitative characterization of water hazard risk is of great significance to guide coal production to be safe.

1. Introduction
Coalfield in China after nearly a century of coal mining, most of the coal mining has entered a deep level, especially in China type coal field, most of the mine has lower carboniferous coal seam mining, upper carboniferous coal seam from the ordovician limestone, the backplane limestone of ordovician limestone karst and often constitute a unified hydraulic system, especially threatened by karst water of coal mine [1]-[3]. With the exploitation of coal resources, the hydrogeological environment of coal occurrence is more complex at present. Statistics have shown that water hazardous accidents are the main accidents restricting the safe production of coal mines. In recent years, there have had 756 coal mine water disaster accidents [4]-[5], resulting in a large number of casualties and huge economic losses. It is still an important basic work to carry out the risk assessment and control of coal mine water disaster in mining. The possibility of coal mine water disaster accidents can be effectively reduced through the classified assessment of the risk and the targeted guidance of construction. Now, the research on coal mine water disaster is gradually transitioning to objectivity and quantification. The effect of safety checklist method [6] and fuzzy comprehensive evaluation method [7] commonly used have shown its inferiority in representing the discreteness of the heterogeneous evaluation index.
system. Meanwhile, the dominant position of human decision making in valuing the weight go against the valid evaluation result.

In the light of the problems above, this article through the factor weights, based on cloud model theory [8] in the cloud and mist phenomenon examine the rationality of the comprehensive weight, contact based on cloud model and matter-element extension theory[9], the fuzziness and randomness of evaluation factor, puts forward the risk level of coal mine water hazards were also contact extension evaluation method of cloud [10], and cloud model calculated the distance between the degree of similarity to judge the trend of the evolution of the flood risk level.

2. Extension connection cloud model theory

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2.1. Matter element extension model method

Matter-element extension model is an organic combination between matter-element theory and extension set theory, which can better deal with the incompatible contradictions among indicators [11]. This model contains a certain evaluation system to determine the classical domain and the nodal domain for the evaluation of the matter-element. According to the extension set theory, the correlation degree of evaluation indexes to different grades can be calculated, to get the quality grade identified by the correlation degree, weight and the comprehensive correlation. The matter element $R_j$ need to be valued combined with the sample $N_j$ of coal mine face, the index parameter $c_i$ of water disaster risk evaluation, and the index state value $v_{ji}$, is as follows:

$$ R_j = (N_j, c, v_j) = \begin{bmatrix} N_j & c_1 & v_{j1} \\ c_2 & v_{j2} \\ \vdots \\ c_n & v_{jn} \end{bmatrix} $$

(1)

The classical domain $R_o$ and nodal domain $R_p$ of the matter element $R_j$ are:

$$ R_o = (N_o, c, v_o) = \begin{bmatrix} N_o & c_1 & <a_{o1}, b_{o1}> \\ c_2 & <a_{o2}, b_{o2}> \\ \vdots \\ c_n & <a_{on}, b_{on}> \end{bmatrix} $$

(2)

$$ R_p = (N_p, c, v_p) = \begin{bmatrix} N_p & c_1 & <a_{p1}, b_{p1}> \\ c_2 & <a_{p2}, b_{p2}> \\ \vdots \\ c_n & <a_{pn}, b_{pn}> \end{bmatrix} $$

(3)

In the formula: According to the correlation function $K_j(X)$ defined by extension set theory and the classical domain and nodal domain, the correlation degree of the matter element to be evaluated is calculated. See the literature for the specific formula (3).

Using correlation degree and weight vector to calculate comprehensive correlation degree, thus, the correlation degree of matter element $N_j$ with respect to disaster class $J$ is determined,
\[ K_j(P) = \sum_{i=1}^{n} u_i K_j(X) \]  

(4)

Compared with the weighted comprehensive correlation degree, the evaluation grade corresponding to the maximum comprehensive correlation degree was taken as the evaluation grade.

2.2. Extension representation of matter element based on the connection cloud.

In order to fully apply the cloud model theory to the evaluation of dangerous water disaster, the applicability of the interval distribution of different grades in the evaluation indexes was improved, and the connection number and cloud model were coupled to form the connection cloud model. Firstly, the grade m and evaluation factor n of the research object were determined, and the set pair theory was applied to the digital features of the connection cloud to generate the i-th grade of evaluation factor J, a connection cloud model with the expected value \( E_Xi \) as the boundary point and the left-right asymmetry, in which the cloud droplet \( X_i \) is generated based on the number of cloud droplets \( N \) and the digital characteristic group \( (E_X, E_n, H, a, k) \), and its determination calculation is shown in formula (5):

\[
u_i = \left[ 1 - \left( \frac{x_i - E_Xi}{a'_i} \right)^2 \right]^{\beta_i}
\]

(5)

\[
k_i = \lg 0.5 / \lg \left[ 1 - \left( \frac{y_i - E_Xi}{a'_i} \right)^2 \right]
\]

(6)

Where, of the left and right half of the hierarchical connection cloud, \( E_Xi \) is the expected value, \( E_n \), the entropy, \( H \), the super entropy; \( L_{\text{max}}^i \), \( L_{\text{min}}^i \) are the upper and lower limit of level i; \( \beta \) is the constant reflecting the cloud blur threshold, generally is 0.01; \( k_i \) is the order of distribution density function corresponding to \( a'_i \); \( y_i \) is \( L_{\text{max}}^i \) or \( L_{\text{min}}^i \).

According to the quantitative representation form of cloud model of evaluation index, the expression of connection cloud and extension matter-element were combined to cope with the problem of factor incompatibility division of extension theory. \( V \) was determined with the help of the digital characteristics of connection cloud to express matter-element. In the light of the risk classification standard of coal mine water disaster, and formula (1) - (6), the cloud digital characteristic value of the level was calculated, and the matter-element extension domain based on connection cloud was constructed as shown in equation (7):

\[
R_{oi} = \begin{bmatrix}
N_i & C_i & (E_{x_i}, E_{n_i}, H_{x_i}, a_i, k_i) \\
\vdots & \vdots & \vdots \\
N_i & C_n & (E_{x_n}, E_{n_n}, H_{x_n}, a_n, k_n)
\end{bmatrix}
\]

(7)

Where \( R_{oi} \) represents the risk grade of water disaster in coal mine; \( C_j \), the evaluation index; \( (E_{x_i}, E_{n_i}, H_{x_i}, a_i, k_i) \), the relation cloud representation of \( R_{oi} \) on \( C_j \).
3. Establishment of Grade Evaluation Model of Water disaster in Coal Mine

Therefore, in this paper, the main factors of water inrush disaster caused by the fracture of coal seam floor were selected as the sample elements, including mining depth, coal seam dip angle, mining thickness, working face, floor pit damage capacity, thickness of aquiclude, water supply intensity, as well as the subjective factors of waterproof safety awareness and waterproof management degree of operators. The purpose of this paper is to fully establish the optimal index set induced by water inrush in the process of coal mine production.

The risk grade of water inrush from coal mine floor was divided into four grades (safe, relatively safe, relatively dangerous and dangerous). The state value of water disaster index was set according to the study of coal mine water disaster characteristics and relevant regulations. The classification standard is shown in Table 1.

| Risk level     | Mining depth | Mining thickness | Coal seam dip angle | Working face length | Floor damage resistance | Thickness of aquiclude | Water supply intensity | Waterproof safety awareness | Site management |
|----------------|--------------|------------------|---------------------|---------------------|-------------------------|------------------------|------------------------|----------------------------|------------------|
| Safe           | ≤50          | <1               | <10                 | ≤100                | >0.8                    | >30                    | >10^2                  | >90                        | >90              |
| Relatively safe| [50,200]     | [1.2]            | [10,20]             | [100,150]           | [0.5,0.8]               | [15,30]                | [10^2,10^4]           | [90,80]                    | [90,80]          |
| Relatively dangerous| [200,400]     | [2,5]            | [20,30]             | [150,250]           | [0.2,0.5]               | [5.15]                 | [10^2,10^6]          | [80,60]                    | [80,60]          |
| Dangerous      | >400         | >5               | >30                 | >250                | <0.2                    | <5                     | >10^6                  | <60                        | <60              |

The weight coefficients of water disaster risk assessment factors were calculated by AHP, entropy weight method and projection pursuit, and the comprehensive weight coefficient was determined by the combination weighting of game theory, the weight calculation results are shown in Table 2.

According to the combination of connection cloud model and extension model, the cloud digital eigenvalues of each evaluation factor can be determined.

Where, when the evaluation index state value is located in the cloud part at both ends, it should be divided into the outer side and the inner side to calculate the determined value of the level respectively. When the determination was 1 in a uniform distribution on the outside of the clouds at both ends, the calculation of the determination on the inside was shown in equation (8):

\[ u_{p,ij} = \left[ 1 - \left( \frac{x_0 - Ex_i}{a_i} \right)^2 \right]^{\frac{1}{2}} \]  

(8)

Where, \( u_{p,ij} \) is the inside determination; \( x_0 \), the end point value of the index classification.
Table 2. Calculation of comprehensive weight

| evaluating indicator | Chromatography | Entropy weight method | Projection pursuit | Comprehensive weight system |
|----------------------|----------------|-----------------------|-------------------|----------------------------|
| X₁                   | 0.118          | 0.113                 | 0.149             | 0.120                      |
| X₂                   | 0.093          | 0.090                 | 0.086             | 0.090                      |
| X₃                   | 0.077          | 0.135                 | 0.103             | 0.110                      |
| X₄                   | 0.107          | 0.120                 | 0.091             | 0.111                      |
| X₅                   | 0.136          | 0.090                 | 0.144             | 0.114                      |
| X₆                   | 0.124          | 0.105                 | 0.078             | 0.108                      |
| X₇                   | 0.090          | 0.105                 | 0.127             | 0.103                      |
| X₈                   | 0.127          | 0.120                 | 0.108             | 0.121                      |
| X₉                   | 0.128          | 0.120                 | 0.115             | 0.122                      |

In this paper, working faces from Feicheng mine (9203 in Caozhuang mine, 7406 in Baizhuang mine, Handan mine (1830 in Wangfeng mine and 1951 in Wangfeng mine), were selected as engineering samples to verify the applicability of the coal mine water disaster risk assessment method based on the extension connection cloud model.

Through the collection of index state value and the investigation and scoring of the safety production of the working face, the data quantification of the water damage evaluation index of each mining face was shown in Table 3.

Table 3. Sample index state value of water disaster on coal mining surface

| working face | X₁/m | X₂/m | X₃/° | X₄/m | X₅  | X₆/m | X₇/m³ | X₈ | X₉ |
|--------------|------|------|------|------|-----|------|-------|----|----|
| 9203 face    | 148  | 1.8  | 18   | 95   | 0.8 | 16   | 1000  | 81 | 77 |
| 7406 face    | 225  | 2.5  | 14   | 130  | 0.6 | 12   | 2000  | 86 | 90 |
| 1830 face    | 308  | 2.8  | 10   | 190  | 0.5 | 7    | 10000 | 73 | 87 |
| 1951 face    | 287  | 3.3  | 10   | 176  | 0.4 | 10   | 3000  | 71 | 77 |

According to the state value of the evaluation index and the extension connection cloud grade membership degree distribution map, the corresponding different grade membership degree cloud droplets in the cloud map are obtained, and the membership value of each grade corresponding to the index state value can be obtained by comprehensive weighting. The comprehensive correlation degree of the grade is calculated by formula (4) to determine the risk grade.

The calculation results of the 1830 samples of the working face are shown in Table 4. The similarity between the risk grade determined by the working face and the two adjacent risk grades is calculated according to the distance similarity principle, as the evolution trend of the water disaster grade to be further determined. The result of disaster water disaster assessment of the sample working face.

Figure. 1 The connection cloud of the evaluation factors of sample
According to the analysis of calculation results in Table 4, compared with the evaluation results of the extension connection cloud model, the results showed that the extension connection cloud is feasible in the evaluation of water disaster grade of coal mine which can reflect the actual situation of the project more accurately. At the same time, compared with BP neural network and other models, the discretization effect of a large number of cloud droplets escaped the calculation results into a local optimal solution, the accuracy of evaluation was improved greatly. The idea of limited interval distribution of cloud model freed the enforced assumption of traditional cloud model for the evaluation of the normal distribution about quality assurance, making the evaluation results more in line with the actual situation.

| Sample | I    | II   | III  | IV   | Evaluation grade | Actual grade | BP Neural network | Evolution trend |
|--------|------|------|------|------|------------------|--------------|------------------|----------------|
| 1      | 0.0567 | 0.3186 | 0.4488 | 0.1004 | III              | III          | IV               | II             |
| 2      | 0.0696 | 0.4963 | 0.4053 | 0.1734 | II               | II           | III              | III            |
| 3      | 0.0163 | 0.1716 | 0.6021 | 0.0539 | III              | III          | III              | IV             |
| 4      | 0.0471 | 0.1997 | 0.3690 | 0.4619 | IV               | IV           | IV               | -              |

4. Conclusion
(1) Based on the relevant research and engineering practice of water disaster characteristics in coal mining face, the risk evaluation factor system of coal mine water disaster was established, and the comprehensive weight method was determined by the game theory which can eliminate the subjectivity of weight calculation.

(2) The feasibility of the extension cloud model in the comprehensive evaluation of the risk level of coal mine water disaster was verified. The problems of fuzziness and randomness at the boundary of the evaluation index classification have been solved. The credibility of the evaluation results was improved, and the evolution trend of the risk based on the principle of distance similarity was used.

(3) Coal mine water disaster risk assessment plays a positive guiding role in guiding coal mine safety mining, and the effective establishment of evaluation index system is the key to accurate evaluation, this paper can further improve the evaluation index system, to dynamically adjust the index weight according to the current state value, so as to further realize the dynamic nature of the evaluation.

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