Research and application of safety assessment method of gas explosion accident in coal mine based on GRA-ANP-FCE*

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Abstract

According to the complexity and nonlinear interaction between influencing factors of gas explosion in coal mine, this paper analyzed the main influencing factors of coal mine gas explosion accident with Grey Relational Analysis, and built the risk assessment index system of coal mine gas explosion based on four factors of “man-machine-environment-management”. This paper built the multi-criterion and multi-level network calculation model for the index system and got the weight sets by using Analytic Network Process. Multi-level fuzzy comprehensive evaluation determined the risk of gas explosion level. A coal mine in the South, for example, its gas explosion risk assessment results showed that the method could find the main key risk factors and deal effectively the complex influence relationship among them, and provide an important reference to coal mine gas accident risk control and management.

Keywords: coal mine; gas explosion; risk assessment; grey relational analysis; analytic network process; fuzzy comprehensive evaluation

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\gamma$</td>
<td>grey relational grade</td>
</tr>
<tr>
<td>$W$</td>
<td>weighted super matrix</td>
</tr>
<tr>
<td>$W^\infty$</td>
<td>limit matrix</td>
</tr>
</tbody>
</table>

1. Introduction

Gas explosion is the main hazard in the safety production activity of our country coal mine. It always threatened to our country mine industry of healthy development because of its characteristics such as heavy damage, more casualty, serious economic losses and so on. According to the latest statistics of State Administration of Work Safety, gas accidents accounted for more than 80% of our country gas accidents, and fatalities accounted for 90% of most serious accidents. To strengthen hazard risk assessment of mine gas explosion which is an important method to prevent and control accident happen, and it has great significance to provide great guarantee for rising safety production of coal mine, and to strengthen the prevention for gas explosion and for reducing the losses by accidents.

There exists many method for analysis and assessment on gas explosion hazard of coal mine, such as Analytic Hierarchy Process(AHP), Fuzzy Analysis Method, Grey Assessment Method, Artificial Neural Network Assessment Method and so on [4-9]. SHI [4] established the non-linear multilevel gray evaluation model of risk assessment of gas explosion accident...
evolution in coal mine based on AHP and gray clustering method. CAO [5] established the risk assessment model of gas explosion in coal mine based on the hazard theory and fuzzy mathematics. Among them, AHP gets the most extensive application in the system decision-making analysis, but the premise of AHP application is that each level or its elements are mutually independent. Because of this, AHP suffers limitation in being used for assessment of complex nonlinear system. Coal mine production is a multi-factor, multivariable and multi-level complex nonlinear system [1-3]. There are many influencing factors to induce mine coal gas explosion in the course of coal mine underground production, and they are interaction and inter-influence. Those uncertain factors can’t be quantized by using traditional mathematical model or science computation. Analytic Network Process (ANP) [10] solved the dependent and feedback between factors and it has been used in selecting scheme and assessing indexes of complex system [11-12].

This paper analyzed the main influencing factors of coal mine gas explosion accident, and built the risk assessment index system of coal mine gas explosion on the basis of four aspects: “man-machine-environment-management”, and built ANP-Fuzzy risk assessment model for coal mine gas explosion by using grey relational analysis (GRA). We built the network model for this assessment indexes to compute the weights distribution by using ANP. At last, we assess the risk of gas explosion in coal mine by using fuzzy comprehensive evaluation (FCE). The result of assessment was in agreement with actual situation and showed that the method would provide an important reference for controlling this risk.

2. GRA of the control factors of gas explosion in coal mine

2.1. Model of GRA

GRA is one of core content of grey theory [14]. Let the index of gas explosion in coal mine was parent factor \(x_0(i)\) and each of influence factors was sub-factor \(x_j(i)\), where \(i = 1,2,...,m, j = 1,2,...,n\), and \(m\) and \(n\) denoted the number of observed values and the number of sub-factors respectively. So, the original data matrix \(X^0 = [x_0(i) \ x_1(i) \ x_2(i) ... \ x_n(i)]\) was composed of the observed values of parent factor and sub-factors. Dimensionless of original data matrix \(X^0\) was done by using equation (1) and we got the dimensionless data \(X\) which was comparable.

\[
x_j(i) = \frac{y_j(i)}{\frac{1}{m} \sum_{i=1}^{m} y_j(i)}
\]

So, the grey relational coefficient of parent factor \(x_0\) and sub-factor \(x_j\) in the \(i\)th position:

\[
\gamma(x_0(i), x_j(i)) = \min_{j} \min_{i} \left[ \frac{\|x_0(i) - x_j(i)\|}{\min_{i} \|x_0(i) - x_j(i)\| + \zeta \max_{j} \max_{i} \|x_0(i) - x_j(i)\|} \right]
\]

(2)

where, \(\min_{j} \min_{i} \|x_0(i) - x_j(i)\|\) is called lower environment parameter, \(\max_{j} \max_{i} \|x_0(i) - x_j(i)\|\) is called super environment parameter and \(\zeta \in [0,1]\) is distinguishing coefficient, usually, \(\zeta = 0.5\).

By focusing the \(\gamma(x_0(i), x_j(i))\) at utter points the algorithm on grey relational grade is as follows equation:

\[
\gamma(x_0, x_j) = \frac{1}{m} \sum_{i=1}^{m} \gamma(x_0(i), x_j(i))
\]

(3)

2.2. Main controlling factors of gas explosion in coal mine

Gas explosion in coal mine would happen in microscopic scales only when the three conditions possess simultaneously that include gas accumulation, fire source and oxygen concentration, and was caused by human production activity in macroscopic view. We analysis the main influence factors of gas explosion in coal mine on basis of four factors of “man-machine-environment-management” combined with gas explosion data in coal mine in south china, and selected 20 qualitative and quantitative indexes, where “non-existence” and “existence” of the qualitative indexes was denoted with 0.5 and 1 respectively. Dimensionless of original data matrix was done by using formula (1) and we calculate the grey relational coefficient using formula (2) and calculate the grey relational grade of each controlling factors by using formula (3). The greater grey relational grade is, the greater influence degree the sub-factors impact on the parent factors and vice versa. The order from big to small of grey relational grade showed as follow: safety investment \(X_5\), safety education \(X_3\), ratio of technical staff \(X_{15}\), safety system \(X_{14}\), staff education standard \(X_1\), safety culture \(X_{12}\), ventilation facilities situation \(X_6\), monitoring facilities situation \(X_7\), distribution of age and seniority \(X_{10}\), air volume supply ratio \(X_2\), mechanization standard
Table 1. Grey associated degree and order of the controlled factors in coal mine gas explosion

<table>
<thead>
<tr>
<th>Factors</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>$x_4$</th>
<th>$x_5$</th>
<th>$x_6$</th>
<th>$x_7$</th>
<th>$x_8$</th>
<th>$x_9$</th>
<th>$x_{10}$</th>
<th>$x_{11}$</th>
<th>$x_{12}$</th>
<th>$x_{13}$</th>
<th>$x_{14}$</th>
<th>$x_{15}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>grade</td>
<td>0.654</td>
<td>0.626</td>
<td>0.704</td>
<td>0.579</td>
<td>0.728</td>
<td>0.644</td>
<td>0.642</td>
<td>0.572</td>
<td>0.588</td>
<td>0.633</td>
<td>0.604</td>
<td>0.649</td>
<td>0.618</td>
<td>0.675</td>
<td>0.690</td>
</tr>
<tr>
<td>Order</td>
<td>5</td>
<td>10</td>
<td>2</td>
<td>14</td>
<td>1</td>
<td>7</td>
<td>8</td>
<td>15</td>
<td>13</td>
<td>9</td>
<td>12</td>
<td>6</td>
<td>11</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

2.3. Establishment of risk assessment indexes of gas explosion in coal mine notes

According to the analysis on influence factors of gas explosion in coal mine with grey relational analysis, we got the main controlling factors. We established the risk assessment indexes shown in Fig 1 by dividing those main controlling factors with four respects of “man-machine-environment-management”. The indexes include four first grade indexes and eighteen second indexes.

3. Analytic network process of the risk assessment indexes of gas explosion in coal mine

3.1. Structure and calculation process of ANP

ANP is an multi-criteria and multi-target system decision-making method which was proposed by professor T.L. Saaty in the 20th century based on AHP [10]. ANP use the similar network structure table to present the relation of object system inner elements, but not the step-by-step hierarchy structure. Aiming at the dependence and feedback features of the step-by-step hierarchy structure which have been in the inner circulation and among hierarchy structure, ANP analyzed the interaction and influence factors and calculated its mixture weights with super matrix. ANP divided system elements into two parts: Control Layer and Network Layer. Fig 2 shows the ANP hierarchical structure diagram including a control layer and network layer.

(1) Determine the single ordering weight of hierarchy elements. Multiple comparisons among the elements of same set were done based on a certain criterion to get the normalized sort weights. In addition, multiple comparisons among the elements of different set were done based on a same criterion to get the weights as well. The multiple comparisons should be done with direct or indirect dominance.

(2) Construction of super matrix. To confirm the relative important degree of each element of network layer, we must compare each elements of network layer under the overall goal and list out multiple judgment matrices. Matrix data surveyed from experts questionnaire and quantified by 1-9 scaling method which was proposed by Saaty [10]. Let that there are $m$ criterions in the control layer of ANP, i.e., $B_1, B_2, \ldots, B_m$, there are $N$ elements in the network layer, i.e., $C_1, C_2, \ldots, C_N$, where $C_i$ has $n$ elements, i.e., $d_{i1}, d_{i2}, \ldots, d_{in}$, $i = 1, 2, \ldots, n$. The normalized feature vector was constructed by the indirect dominant which compared the size of influence between the element of $C_i$ and $d_{ij}$ of $C_j$. The normalized feature vector is:

$$ w^T_{ij} = \begin{bmatrix} w_{i1}^{(j)} & w_{i2}^{(j)} & \ldots & w_{in}^{(j)} \end{bmatrix}^T $$

(4)
A new matrix $W_{ij}$ as equation (5) was made up with the priority vector that compared $C_i$ element to $C_j$ element with its influence. Then, super matrix W was showed as follow equation (6).

$W_{ij} = \begin{bmatrix}
    w_{i1}^{(j1)} & w_{i1}^{(j2)} & \cdots & w_{i1}^{(jn)} \\
    w_{i2}^{(j1)} & w_{i2}^{(j2)} & \cdots & w_{i2}^{(jn)} \\
    \vdots & \vdots & \ddots & \vdots \\
    w_{in}^{(j1)} & w_{in}^{(j2)} & \cdots & w_{in}^{(jn)}
\end{bmatrix}$  \hspace{1cm} (5)

$W = \begin{bmatrix}
    W_{11} & W_{12} & \cdots & W_{1N} \\
    W_{21} & W_{22} & \cdots & W_{2N} \\
    \vdots & \vdots & \ddots & \vdots \\
    W_{N1} & W_{N2} & \cdots & W_{NN}
\end{bmatrix}$ \hspace{1cm} (6)

(3) Calculation of weighted super matrix $\overline{W}$. Each sub-block $W_{ij}$ of super matrix was normalized, but super matrix was not. Therefore, we need construct a weighted super matrix in order to handle super matrix with column normalized. Compared each group elements’ importance with $C_j$ based on $B_s$ criterion, we can get a normalized priority vector: $A_j = [a_{ij} \ldots a_{nj}]^T$. Then the weighed matrix of the first grade indexes is $A = [A_1 \ldots A_N]^T$. And now, the weighted super matrix $\overline{W} = A^*W$.

(4) Calculation of limit matrix $W^*$. The limit matrix is the result of stability treatment of the weighted super matrix, namely $k$ power of the weighted super matrix. If the limit exist when $k \to \infty$, we get $W^*$ that is a long-term stable matrix. By now, nonzero value in each row of $W^*$ is same, namely the weights for the element of network.

3.2. Analysis on the risk assessment indexes with ANP

We established network structure of the Indexes system and calculated its weights distribution with SuperDecisions (SD) which is the software for ANP. We input the judgment matrixes of first and second grade indexes into SD and get the super matrix, weighted super matrix and limit matrix after it passed consistency checking.

After calculation, we get the weight of first grade index $W=\{0.2479, 0.1244, 0.0509, 0.5767\}$ and the weight of second grade index $W^*=\{0.0937, 0.0314, 0.1229, 0.0169, 0.0525, 0.0398, 0.0098, 0.0056, 0.0004, 0.0125, 0.0123, 0.0231, 0.0018, 0.0007, 0.1034, 0.1397, 0.2665, 0.0670\}$. After $W^*$ was normalized, we get $W_1=\{0.3778, 0.1266, 0.4957\}$, $W_2=\{0.1357, 0.4216, 0.3191, 0.0789, 0.0447\}$, $W_3=\{0.0079, 0.2461, 0.2419, 0.4538, 0.0361, 0.0141\}$ and $W_4=\{0.0179, 0.2422, 0.4622, 0.1162\}$.

4. Multi-lever fuzzy comprehensive evaluation of gas explosion risk in coal mine

Multilevel fuzzy comprehensive evaluation is a method which evaluates comprehensively membership degree of evaluated objects from many factors and is based on fuzzy relation synthesis principle. It includes four base elements: index set, comment set, judgment matrix and weights set. It’s concrete step as followings [13]:

![Diagram of ANP network structure](image)

Fig. 2. The network structure of ANP.
(1) Building index set $U = \{ u_1, u_2, ..., u_m \}$ of evaluated object system, and $U = \{ u_1, u_2, ..., u_m \}$. According to Fig 1, we let $U_1 = \{ \text{personal factor, equipment factor, environment factor, management factor} \}$, $U_2 = \{ \text{staff education standard, distribution of age and seniority, ratio of technical staff} \}$, $U_3 = \{ \text{mechanization standard, ventilation facilities situation, monitoring facilities situation, dust-proof facilities situation, flame-proof facilities situation} \}$, $U_4 = \{ \text{coal seam geological structure, coal seam gas content, gas emission, air volume supply ratio, spontaneous combustion period, coal dust explosion index} \}$ and $U_5 = \{ \text{safety system, safety education, safety education, safety investment, safety culture} \}$.

(2) Calculation the weight set $W$ and definition comment set $V$. Where, $W$ is shown in section 3.2, $V = \{ \text{Safe, more safe, general safe, general not safe, not safe} \}$, the corresponding values is $\{5, 4, 3, 2, 1\}$.

(3) Construction the judgment matrix $R = \begin{bmatrix} r_{11} & r_{12} & ... & r_{1m} \\ r_{21} & r_{22} & ... & r_{2m} \\ ... & ... & ... & ... \\ r_{n1} & r_{n2} & ... & r_{nm} \end{bmatrix}$, where $r_{ij}$ is the membership of $V_j$ corresponding $U_i$ of $U$, namely the evaluated object was evaluated as $V_j$ from the angle of the index $U_i$. Therefore, $r_{ij}$ was the single evaluation of this evaluation object. We analyzed and calculated the expert judgment table, and normalized its result with $K$.

$$K = \sum_{j=1}^{K} r_{ij}.$$ Where, $K$ is the number of elements of comment set. The 1st grade fuzzy judgment matrix and its normalized matrix showed as followings:

$$R_1 = \begin{bmatrix} 0 & 1 & 4 & 12 & 3 \\ 1 & 1 & 2 & 12 & 6 \\ 0 & 1 & 2 & 13 & 6 \end{bmatrix} \rightarrow \begin{bmatrix} 0.00 & 0.05 & 0.20 & 0.60 & 0.15 \\ 0.05 & 0.05 & 0.10 & 0.60 & 0.20 \\ 0.00 & 0.00 & 0.05 & 0.65 & 0.30 \end{bmatrix}$$

(4) Selection composite operator to process the multilevel fuzzy comprehensive evaluation. At first, we would get comprehensive evaluation vector $B_i$ from evaluating comprehensively to sub-goal of the object based on formula $B_i = W \circ R_i$. The judgment matrix $R$ was composed of each evaluation vectors of sub-goal, and calculated the evaluation vector $R$ of the general goal. Where $W_i$ and $r_i$ was the weight vector of the $i$th sub-goal and judgment matrix respectively, and $A$ was the weight vector of the first grade index, and ‘$\circ$’ was the composite operator.

To make the assessment results to preferably embody the overall characteristic of assessed object, we use operator $M(\bullet, \oplus)$ which is the weighted mean model. The results showed as followings:

$$B_1 = W_1 \circ R_1 = \begin{bmatrix} 0.3778 \\ 0.1266 \\ 0.4957 \end{bmatrix}^{T} \begin{bmatrix} 0.00 & 0.00 & 0.20 & 0.60 & 0.15 \\ 0.05 & 0.05 & 0.10 & 0.60 & 0.20 \\ 0.00 & 0.00 & 0.05 & 0.65 & 0.30 \end{bmatrix} = \begin{bmatrix} 0.0063 \\ 0.0252 \\ 0.1130 \\ 0.6248 \\ 0.2307 \end{bmatrix}$$

Likewise,

$$B_2 = \begin{bmatrix} 0.0644 \\ 0.2264 \\ 0.3868 \\ 0.5776 \\ 0.4548 \end{bmatrix}$$

$$B_3 = \begin{bmatrix} 0.0419 \\ 0.1390 \\ 0.1990 \\ 0.3270 \\ 0.2391 \end{bmatrix}$$

$$B_4 = \begin{bmatrix} 0.0231 \\ 0.0419 \\ 0.2045 \\ 0.4506 \\ 0.1185 \end{bmatrix}$$

Then, the judgment matrix of the 2nd grade fuzzy comprehensive evaluation is composed of $B_1, B_2, B_3$ and $B_4$, namely $R = [B_1, B_2, B_3, B_4]^{T}$. The result showed as follow:

$$B = W \circ R = \begin{bmatrix} 0.0250 \\ 0.0657 \\ 0.2042 \\ 0.5033 \\ 0.1971 \end{bmatrix}$$

At last, we calculated the assessment value $V$ of ANP-Fuzzy:

$$V = B \circ V^{T} = \begin{bmatrix} 0.0250 & 0.0657 & 0.2042 & 0.5033 & 0.1971 \end{bmatrix} \begin{bmatrix} 2 & 3 & 4 & 5 \end{bmatrix}^{T} = 3.7675$$

Because the result is close to 4 of comment set, we think that the assessed system is more-safe. The result is consistent with actual situation.

5. Conclusions

(1) After the analysis on the influence factors of gas explosion in coal mine with GRA, we not only get the grey relational grades and its order but also it will provide strong support to build risk assessment indexes of gas explosion in
coal mine. Meanwhile, the results showed that the personal and management factor are the main controlling one to gas explosion accident, the machine and environment secondly.

(2) The network calculation model built by ANP, not only embody the dependency relationship among each factors but also represent it qualitatively and quantitatively. The calculation results ANP showed that both personal and management factor make the most important role of gas explosion in coal mine, and the weights of them are more than 80% of all of weights. Therefore, improving the management standard and training the staff qualities are the important way to raise the safe management standard in coal mine.

(3) With the example verification, the result of it showed that the method combined with GRA, ANP and FCE is feasible to assess the gas explosion risk in coal mine and provide a new method and way to assess scientifically.

References