Application of Fuzzy Mathematical Analysis Method in the Evaluation of Coal Mine Gas System

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Abstract: Mine gas system largely determines the safety of coal mine. Therefore, it is of great practical significance to evaluate the safety of mine gas system accurately. This study aims to establish a scientific gas evaluation system and improve the safety of mine. In this paper, the safety of mine gas system is evaluated accurately; besides, the selecting method of evaluation index system, the construction method of mathematical model and the evaluation grade are determined according to the actual situation. The safety evaluation system of the gas system is established by using the analytic hierarchy process; the index weight is calculated by using the maximum eigenvalue. The consistency test of indexes is also passed. Finally, the mathematical model is verified by an example. The result shows that the fuzzy mathematical model can be used to evaluate the safety of the gas system in a better way, thus improving the safety factor of the whole mine.

Key words: coal mine gas system; analytic hierarchy process; fuzzy comprehensive evaluation; system safety evaluation; consistency test

1. INTRODUCTION

Among the five major causes that endanger coal mine safety, namely, water, fire, roof, gas and coal dust, gas accounts the absolute proportion. According to official statistics, the greater the number of deaths in the coal mine accident, the greater the proportion of gas accidents; in the coal mine accidents with more than 10 deaths, the gas accidents reaches over 90% [1]. Mine gas explosion is generally characterized by strong abruptness and great damage, which can not only cause huge economic losses, but also lead to death and coal mine destruction, and even bring bad political impact and social unrest.

As a complex dynamic system, coal mine gas system is influenced by many factors. If it can be rigorously evaluated, problems exist can be discovered timely, the appropriate adjustment and transformation measures can also be taken. As a result, the gas accidents can be reduced, and it'll be convenient to manage the gas system.

The possibility of gas explosion can be greatly increased if the following three conditions are met: the gas concentration lies in the explosion limit [3], the oxygen concentration is not less than 12% of the mixed air, and there is combustion source with the temperature between 650℃to750℃[4]. As a matter of fact, many accidents will not occur if they are forecasted and good preventive measures are taken. However, a series of preventive work can't be conducted due to backward technology and the low educational level of staff, coupled with the fluke minds of bad merchants and workers. With the rapid development of economy, the demand for coal is growing, but the uncontrolled mining has increased the difficulty. Hence, how to prevent the occurrence of mine accidents has become the most urgent problem that needs to be resolved. This paper studies the serious problem, and analyzes the factors that affect the mine gas system. First of all, the content of safety evaluation is determined based on the analysis of practical problems; secondly, the safety evaluation method is selected according to actual needs; thirdly, the safety evaluation index system of mine gas system is established on the above basis; finally, an example is given to verify whether the fuzzy evaluation model is reasonable. In this way, coal workers' personal safety can be guaranteed, and references can also be provided to administrative departments, so that they are able to monitor the coal industry and understand the current status of coal mine gas system.

2. DETERMINATION OF MINE GAS SYSTEM EVALUATION METHOD

The mine gas system consists of many equipment, machineries and geological environment, and is a complex dynamic system that influenced by interrelated and mutually constrained factors. Most of the factors are qualitative variables rather than quantitative variables, which lead to ambiguity in the safety evaluation. Therefore, we should combine the quantitative analysis with the qualitative analysis in the fuzzy mathematical approach, in order to make a comprehensive evaluation on the safety of the gas system.

In view of the large number of influencing factors, the expert consultation method is adopted to select the preliminary index, and then calculate the correlation coefficient matrix between the indexes. Generally, the less relevant indexes are selected to constitute the evaluation index system, with the purpose to reduce the impact of redundant information on the evaluation process. The impact of different indexes on the evaluation objects can be varied. In the multi-index comprehensive evaluation, different weight values should be given with different indexes. The determination of effective weight coefficient has a direct impact on the reliability and rationality of the evaluation results. Currently, correlation coefficient method, factor analysis method, analytic hierarchy process, expert evaluation method and index value method are the most commonly used weight coefficient determination methods. In this paper, based on the characteristics of gas system, the analytic hierarchy process is used to analyze complex problems, and then the corresponding countermeasures are put forward according to the research results.

According to the tree hierarchy model established in Figure 1, a reasonable scale of qualitative factors is given. In order to further facilitate the smooth conduct of decisions, some standards need to be given here. Besides, unified standards are in demand in order to compare evaluation indexes of the same level and give the judgment matrix, as shown in the following table [9]:

Table 1 Factors of Judgment Matrix and Their Significance

Scale	Meaning
1	It indicates that factor A and factor B share the same effect
3	It indicates that factor A and factor B share the same effect, and the difference is negligible
5	It indicates that factor A and factor B share the same effect, and the difference is large
7	It indicates that factor A and factor B share the same effect, and the difference is considerable
9	It indicates that factor A and factor B share the same effect, and the difference is extremely great

Then, the judgment matrix is constructed. Assuming that factor a_k in the A-layer is related to the factors $A_1, A_2, A_3, ..., A_n$ in the next layer, the general form of the constructed judgment matrix is as follows:

$$\begin{array}{ccccc} a_k & A_1 & A_2 & \cdots & A_n \\ A_1 & a_{11} & a_{12} & \cdots & a_{1n} \\ A_2 & a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & & \vdots \\ A_n & a_{n1} & a_{n2} & \cdots & a_{nn} \end{array}$$

It obtains the judgment

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}$$

In the following, the weight of each factor is calculated according to the judgment matrix *A*. By using matlab, we can quickly calculate the largest eigenvalue of *A* matrix, and the corresponding feature vector, which shall be used as the weight vector. Finally, in order to ensure the rationality of the method and the reliability of the results, it is necessary to judge whether the maximum eigenvalue can pass the consistency test. The comparison expression is as follows:

$$C \cdot I = \frac{\lambda_{\max} - n}{n-1} (n > 1), C \cdot R = \frac{C \cdot I}{R \cdot I}$$

Wherein, the order of *A* is indicated as n , the average of the consistency evaluation indexes is indicated as $R \cdot I$, in order to eliminate the possible effects of the maximum and minimum errors on the results. The values can be found in Table 2 in Reference [9]. If the value of C.R is greater than or equal to 0.1, we have reason to believe that it doesn't pass the consistency test and needs to be adjusted until the value of C.R is less than 0.1.

3. FUZZY COMPREHENSIVE EVALUATION OF GAS SYSTEM

Method that conducts overall judgment on multiple programs or things that involve the influence of fuzzy-related factors is called fuzzy comprehensive judgment, which is also known as fuzzy comprehensive evaluation. It was first proposed by Professor Wang Peizhuang. The principle is to calculate the judge matrix of each factor that related to the judged target based on fuzzy transformation theory; the maximum membership principle is used as the standard to carry out overall evaluation on the target.

According to the index layer contained in the model, it is necessary to adopt the multi-level fuzzy comprehensive evaluation to get the corresponding conclusion. First, a variety of factors are classified. To tell the truth, different categories can be divided into by different authors, but the basic basis is the factor membership. So the difference range is not large. And then the classified factors are given with influencing factors according to the selected criteria. Finally, according to our given judgment matrix, a similar method is used to carry out fuzzy comprehensive evaluation on factors of the upper level. The process is as follows:

(1) To determine the set *U*. The factors set *U* will be divided into several factors sub-sets, in order to

facilitate the next step of work. It is recorded as:

$U = \{U_1, U_2, U_3, ..., U_i, ..., U_n\}(i = 1, 2, 3, ..., n)$

Wherein, U refers to the i^{th} factor of the first layer, while U is the determined by the m^{th} factor in the second layer.

$U_i = \{U_{i1}, U_{i2}, U_{i3}, ..., U_{ij}, ...U_{im}\}$

Wherein, U refers to the j^{th} factor of the second layer, while U is the determined by the q^{th} factor in the second layer.

$U_{ij} = \{U_{ij1}, U_{ij2}, U_{ij3}, ..., U_{ijq}\}(q = 1, 2, 3...)$

(2) Giver the factor a corresponding weight. In other words, the factor is given with a weight according to its importance among the factors of this layer, which is indicated as follows:

The first layer

$A = \{a_1, a_2, a_3, ..., a_i, ...a_n\}(i = 1, 2, 3, ..., n)$

The second layer

$A_i = \{a_{i1}, a_{i2}, a_{i3}, ..., a_{ij}, ..., a_{im}\}(j = 1, 2, 3, ..., m)$

The third layer

$A_{ij} = \{a_{ij1}, a_{ij2}, a_{ij3}, ..., a_{ijq}\}(q = 1, 2, 3, ...)$

(3) Establish the evaluation set V. The evaluation set, as a collection, is composed of different numerical values. The value evaluation refers to the various evaluation results that possibly made for each evaluation subject. Its general form can be expressed as:

$V = \{V_1, V_2, V_3, ..., V_P\}(P = 1, 2, 3, ...)$

From the successful cases in the past, it can be seen that the number P is usually between 3 and 7. If the value of P is too large, it shall not be understood nor expressed generally, just like the fact that it is not easy to draw a four-dimensional space on the plane, resulting in difficulties in the evaluation process; but if the value of P is too small, that is, the sample is too small, although the difficulty of evaluation will be greatly reduced, the evaluation results are not accurate.

(4) Fuzzy comprehensive evaluation. In view of the fact that each factor in the first layer is determined by the factors in the second layer, it is natural that the evaluation results of the first layer can be easily calculated once the results of the next layer are obtained. For the sake of convenience, the judgment matrix of the second layer is indicated as R_i , and has the following form:

$$R_i = \begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1n} \\ r_{i21} & r_{i22} & \cdots & r_{i2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{in1} & r_{in2} & \cdots & r_{inp} \end{bmatrix}$$

The number of j in U_{ij} determines the matrix line number of R_i , the fuzzy comprehensive evaluation set is indicated as

$$B_i = A_i \circ R_i = [a_{i1}, a_{i2}, ..., a_{in}] \circ \begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1n} \\ r_{i21} & r_{i22} & \cdots & r_{i2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{in1} & r_{in2} & \cdots & r_{inp} \end{bmatrix} = \left[b_{i1}, b_{i2}, ..., b_{in}\right]$$

Wherein, "$\circ$" refers to a fuzzy operator.

4. EXAMPLE ANALYSIS

In view of the fact that the mine gas disaster prevention and control is largely related to the gas system, so it is quite essential to evaluate the reliability of the gas system, not to mention that it can further provide a basis for the effective use of gas. In this paper, a coal mine in Shanxi Province is used as an example to validate the gas system evaluation model. According to the steps of comprehensive evaluation method proposed above, it is possible for us to determine whether the gas drainage system of the coal mine is safe, and whether there is a safety hazard in the gas facilities, so as to provide the reference for further management. The results are as follows:

Table 2 Safety Evaluation Table of a Coal Mine Gas System in Shanxi Province

Level 1 Index	Level 2 Evaluation Index	Weight	Level 2 Score	Level 1 Score
Environment of extraction system	Gas extraction rate	One-vote veto	1	0.79
	Gas extraction amount	One-vote veto	1	
	Gas contained condition in the coal seam	0.19	0.6	
Pumping facilities safety	Extraction pump	0.27	0.94	0.85
	Meter regulator	0.11	0.6	
	Safety monitoring system	0.08	0.9	
Extraction system safety	Annual plan of gas extraction	One-vote	1	0.83

management		veto		
	Personnel quality	0.08	0.8	
	Mine management system	0.13	0.9	
Potential accident control of gas system	Wind speed of mining face	One-vote veto	1	0.78
	Average gas over-limit number of monthly mining	0.3	0.8	
	Intact rate of gas monitoring equipment	0.06	0.9	

According to the actual situation of the system, when the evaluation system established in this paper is used to evaluate the safety of a coal mine gas extration system in Gansu, the assignment is shown as the above table. According to the calculation formula, the comprehensive evaluation value of the safety of a coal mine gas extraction system in Gansu is 0.809> 0.8, so the coal mine gas system is safe to a certain extent.

5. CONCLUSION

In this paper, after taking into full consideration the actual situation of coal mine production, a hierarchical model of Figure 1 is established according to the truth that its general characteristics are in line with the fuzzy mathematical model. And then, each factor in the mine gas system is given with a weight based on unified standards, which constitutes the basic factor in multi-layer fuzzy evaluation system; besides, the fuzzy comprehensive evaluation method of the mine gas system is described in detail. The fuzzy comprehensive evaluation method of the mine gas system is described in detail. Finally, an example is adopted to illustrate the application of the method in the actual system. The results show that the method can evaluate the safety of the gas system in a better way, so it has high practical application value.

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