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Safety Evaluation of Mine Pressure Based on Dynamic Fuzzy Theory

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Abstract: The fuzzy is existed between safety grades of mine pressure. Using dynamic fuzzy theory to evaluate safety state of mine pressure is proposed in the study. For the deficiency that weight is determined by expert knowledge in fuzzy evaluation, the weight of evaluation index is dynamically set according to influence degree of evaluation index on mine pressure state in the study. Through analyzing pressure monitoring data, the accuracy is 85% for evaluation of mine pressure safety; therefore, the mine pressure evaluation method based on dynamic fuzzy theory proposed in the study is accurate and effective.

Key words: Coal mine, mine pressure, safety evaluation, fuzzy evaluation

INTRODUCTION

With the depth and the scale of coal mine exploitation, rock burst hazards become more and more serious. The safety problem of mine pressure has become an important issue that is needed to be resolved urgently. In order to solve rock burst, coal mine has invested a lot of money to build a variety of mine pressure monitoring systems, which monitor mine pressure data (such as working resistance of hydraulic prop, roof separation, anchor stress, electromagnetic radiation, etc.,). Through these monitoring data, the safety state of mine pressure is determined. For example, the value of electromagnetic radiation is less than 30 mV, it is safe and the value of electromagnetic radiation is more than or equal to 30 mV, it is unsafe. The data is fuzzy and there is no significant difference in value, thus the compulsory division is clearly unreasonable. From one grade to another adjacent grade, the difference is not obvious and no clear boundary is existed between grades. This is a continuous transition process from quantitative transition to qualitative transition. Non-deterministic in division is fuzzy (Fu *et al*., 2011).

Fuzzy set theory provides a powerful mathematical tool for fuzzy uncertainty problem, which translate "uncertainty" into "certainty" through making membership function as intermediary. Fuzzy evaluation is a comprehensive evaluation method based on fuzzy math, using fuzzy relation to quantify ill-less quantifiable factors.

There are many emergencies in coal mine and various factors are interacted, therefore, a number of fuzzy factors are involved in mine pressure safety evaluation. Because fuzzy evaluation method can quantify fuzzy parameters, fuzzy evaluation method in theory can obtain a better evaluation result for mine pressure safety evaluation. For the deficiency that weight is determined by expert knowledge in fuzzy evaluation, a dynamic fuzzy evaluation method is proposed that the weight of evaluation index is dynamically set according to influence degree of evaluation index on mine pressure state in the study.

DYNAMIC FUZZY EVALUATION METHOD

Dynamic fuzzy evaluation method is that using fuzzy math evaluate object influenced by many factors according to certain standard (Zhou and Shi, 2009; Su *et al*., 2008; Zhang *et al*., 2011). Steps are as follows:

- **Determine evaluation index set:** Characteristics of monitoring parameters are extracted that are influence on mine pressure safety and select n monitoring parameters that are greater influence on mine pressure safety to constitute evaluation index set $U = \{u_1, u_2, ..., u_n\}$
- **Determine evaluation grade:** If object has m evaluation grades, which constitute evaluation set $V = \{v_1, v_2, ..., v_m\}$, each grade corresponds to a fuzzy subset
- **Establish fuzzy relation matrix:** Let R is a fuzzy relationship from U to V, $U \times V \rightarrow [0, 1]$ and R can be represented by n×m matrix in [0, 1] interval. The transformation determined by R is as follows in Table 1

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Table 1: Standard of mine pressure safety grade

Grade	Hydraulic prop	Electromagnetic radiation	Anchor stress	Roof separation
□	5	10	140	15
□	10	20	120	30
□	15	30	100	45
□	20	40	80	60
□	25	50	60	75

r_{ij} is degree of fuzzy relationship between u_j and v_i, which means degree of index i evaluated to grade j.

$$r_{ij} = \begin{cases} 0 & c_i \le s_{i,j-1}, c_i \ge s_{i,j+1} \\ \dfrac{c_i - s_{i,j-1}}{s_{ij} - s_{i,j-1}} & s_{i,j-1} < c_i \le s_{ij} \\ \dfrac{c_i - s_{i,j+1}}{s_{ij} - s_{i,j+1}} & s_{ij} < c_i < s_{i,j+1} \end{cases} \quad (1)$$

and:

$$r_{i1} = \begin{cases} 1 & c_i \le s_{i1} \\ \dfrac{c_i - s_{i2}}{s_{i1} - s_{i2}} & s_{i1} \le c_i < s_{i2} \\ 0 & c_i \ge s_{i2} \end{cases} \quad (2)$$

$$r_{im} = \begin{cases} 0 & c_i \le s_{i,m-1} \\ \dfrac{c_i - s_{i,m-1}}{s_{im} - s_{i,m-1}} & s_{i,m-1} < c_i \le s_{im} \\ 1 & c_i \ge s_{i,m} \end{cases} \quad (3)$$

where, c_i is measured value of index i, $s_{i,j-1}$, $s_{i,j}$, $s_{i,j+1}$ are evaluation standards of index i that belongs to grade $s_{i,j-1}$, $s_{i,j}$, $s_{i,j+1}$, respectively

- **Determine the weight of fuzzy evaluation index:** It is a key problem of fuzzy evaluation that reasonably determines the weight of evaluation index in practical applications, because it reflects the proportion of various indexes in evaluation process. Generally determining weight methods are experienced judgment method, weighted statistical method, fuzzy coordinated weight distribution method and fuzzy relation equation method, etc. Because the influence of variety evaluation indexes on mine pressure is different and the geological condition of different coal mines is different, the weight of fuzzy evaluation index is dynamically calculated using evaluation sample set in the study

  If evaluation sample set has l test samples and each sample has n evaluation indexes and x_{ij} is the index of sample i evaluating grade j, average value of each index in test sample set is as follows:

Table 2: Fuzzy weight of each evaluation index

Index	Weight	Average	Minimum	Maximum
u_1	ù$_1$	$Savg_1$	min_1	max_1
u_2	ù$_2$	$Savg_2$	min_2	max_2
...	...	...	...	...
u_n	ù$_n$	$Savg_n$	min_n	max_n

$$Savg_j = \frac{1}{l}\sum_{i=1}^{l} x_{ij} \quad (4)$$

The maximum and minimum value of safety evaluation index is obtained from Table 2

The weight of each evaluation index is calculated according to the degree that evaluation index is influence on mine pressure

The weight of evaluation index which smaller value is better, such as electromagnetic radiation, etc. is calculated by Eq. 5:

$$\varpi_i = \frac{min_i}{Savg_i} \quad (5)$$

The weight of evaluation index which bigger value is better, such as anchor stress, etc. is calculated by Eq. 6:

$$\varpi_i = \frac{Savg_i}{max_i} \quad (6)$$

where, ϖ_i is the weight of evaluation index i, $Savg_i$, min_i and max_i are the average, minimum and maximum value of evaluation index i in sample set, respectively

Weight vector of evaluation index $W = (\varpi_1, \varpi_2, ..., \varpi_n)$ can be obtained. In order to ensure that the sum of each evaluation index's weight is 1, the weight of each index must be normalized before fuzzy composite operation. Normalization equation is as follows:

$$\varpi_i = \frac{\varpi_i}{\sum_{i=1}^{n} \varpi_i} \varpi_i > 0 \; i = 1, 2, ..., n \quad (7)$$

- **Select the appropriate composite operator ⊙:** Weight of evaluation index W and fuzzy relationship matrix R are composed and the fuzzy comprehensive evaluation results of each test sample can be obtained:

$$R = (\omega_1, \omega_2, \cdots, \omega_n) \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \odot \quad (8)$$

where, y_i is calculated by compositing W and column J of R, which means the membership degree of test sample on grade v_j

- To analyze fuzzy comprehensive evaluation result, the final evaluation result is obtained

DYNAMIC FUZZY EVALUATION MODEL IN MINE PRESSURE SAFETY EVALUATION

With the depth and the scale of coal mine exploitation, rock burst hazards become more and more serious, which seriously affect safety production in coal mine. Based on mine pressure control standards of "Coal Mine Safety Regulations", using weighted fuzzy evaluation method, pressure monitoring data collected from coal mine in Beijing Coal Group is analyzed in order to find the relationship between coal mine monitoring data and safety state and guide safety production in coal mine (Song *et al*., 2007; Du *et al*., 2000). To validate the proposed algorithm, the test sample set which are selected 4 samples from each safety grade data collected from coal mine in Beijing Coal Group is made evaluation. The sample data is shown in Table 3.

To analyze pressure monitoring data of coal mine in Beijing Coal Group in recent years, hydraulic prop, electromagnetic radiation, anchor stresses and roof separation 4 factors are selected as coal mine pressure safety decision-making indexes and safety grade of mine pressure is divided into safety, relative safety, alarm, relative danger and danger. When mine pressure state is evaluated as danger grade, work must be stopped, then adopt measures to deal with danger (Mu *et al*., 2010; Xu *et al*., 2010; Chen *et al*., 2008). The smaller the value of Hydraulic prop, electromagnetic radiation and roof separation are, the better they are; while the bigger the value of anchor stress is, the better it is. According to "Coal Mine Safety Regulations", 4 evaluation indexes are divided into 5 safety grades. It is shown in Table 4.

The dynamic fuzzy evaluation process is as follows:

- **Determine evaluation index:** Characteristics of mine pressure monitoring parameters influencing mine pressure safety state are extracted and among them hydraulic prop, electromagnetic radiation, anchor stress and roof separation 4 parameters are selected as coal mine pressure safety evaluation indexes

  Let x1~x4 represent as 4 evaluation indexes, that are hydraulic prop (x1), electromagnetic radiation (x2), anchor stress (x3), roof separation (x4)

Table 3: Sample data

Sample	Hydraulic prop	Electromagnetic radiation	Anchor stress	Roof separation	Safety grade
1	4.8	11	142.6	13	I
2	4.2	7	118.2	12	I
3	7.6	8	140.4	14	I
4	4.5	12	164.8	11	I
5	8.2	14	119.2	20	II
6	8.9	16	129.3	26	II
7	10.2	12	124.5	25	II
8	9.7	17	118.4	28	II
9	14.0	25	98.5	32	III
10	12.3	20	110.4	34	III
11	14.2	26	103.6	45	III
12	13.8	32	106.2	38	III
13	12.5	37	81.3	58	IV
14	15.4	28	79.6	46	IV
15	19.1	36	84.2	65	IV
16	18.5	34	86.7	64	IV
17	28.6	56	76.9	72	V
18	24.2	37	76.7	60	V
19	34.1	48	78.6	76	V
20	23.5	50	77.2	59	V

Table 4: Divisions of mine pressure safety grades

Hydraulic prop (Mpa)	Electromagnetic radiation (mV)	Anchor stress (kN)	Roof separation (mm)	Safety grade
<5	<10	>140	<15	I
5~10	10~20	120~140	15~30	II
10~15	20~30	100~120	30~45	III
15~20	30~40	80~100	45~60	IV
>20	>40	<80	>60	V

- **Establish evaluation set:** According to divisions of coal mine pressure safety grades shown in Table 4, safety grade of mine pressure can be divided into safety, relative safety, alarm, relative danger and danger 5 grades. Evaluation set can be expressed as V = {I, II, III, IV, V}. Because fuzzy evaluation method use specific grade standard of indexes as reference, it is necessary to transform grade of indexes in Table 4, that the reference standard of grade I~IV is the maximum value of each grade range and the reference standard of grade V is obtained by I~IV arithmetic sequence. The standard of mine pressure safety grade is as shown in Table 5
- **Establish fuzzy evaluation matrix:** The standard of evaluation index is different, that the smaller value of hydraulic prop, electromagnetic radiation and roof separation (x1, x2, x4) is better and the bigger value of anchor stress (x3) is better. Because evaluation index and safety grade of mine pressure are fuzzy, boundaries of safety grade are characterized by membership function. From the standard of pressure safety grade in Table 5, the membership function of 5 grades can be obtained

  For example, the membership function of hydraulic prop is as follows:

Table 5: Standard of mine pressure safety grade

Safety grade	Hydraulic prop	Electromagnetic radiation	Anchor stress	Roof separation
I	5	10	140	15
II	10	20	120	30
III	15	30	100	45
IV	20	40	80	60
V	25	50	60	75

Table 6: Dynamic fuzzy evaluation result of samples

Sample	Level □	Level □	Level □	Level □	Level □	Safety grade
1	0.9819	0.0180	0	0	0	I
2	0.5646	0.3961	0.0391	0	0	I
3	0.8973	0.1026	0	0	0	I
4	0.9639	0.0360	0	0	0	I
5	0.3038	0.6787	0.0174	0	0	II
6	0.3678	0.6321	0	0	0	II
7	0.3045	0.6875	0.0078	0	0	II
8	0.0908	0.8743	0.0348	0	0	II
9*	0	0.2915	0.5855	0.0326	0	III
10	0	0.6503	0.3496	0	0	II
11	0	0.1821	0.7096	0	0	III
12	0	0.2695	0.5500	0	0	III
13	0	0.0987	0.1519	0.5689	0	IV
14	0	0.0360	0.3560	0.4548	0.0087	IV
15	0	0	0.1269	0.6303	0.0622	IV
16	0	0	0.2050	0.5647	0.0498	IV
17	0	0	0	0.4052	0.5947	V
18*	0	0	0	0.5819	0.2376	IV
19	0	0	0	0.4048	0.5590	V
20*	0	0	0.0124	0.6080	0.3795	IV

$$u_1(x)=\begin{cases}1 & x\le 5\\ (10-x)/5 & 5<x\le 10\\ 0 & x>10\end{cases}$$

$$u_2(x)=\begin{cases}0 & x\le 5, x>15\\ (x-5)/5 & 5<x\le 10\\ (15-x)/5 & 10<x\le 15\end{cases}$$

$$u_3(x)=\begin{cases}0 & x\le 10, x>20\\ (x-10)/5 & 10<x\le 15\\ (20-x)/5 & 15<x\le 20\end{cases}$$

$$u_4(x)=\begin{cases}0 & x\le 15, x>25\\ (x-15)/5 & 15<x\le 20\\ (25-x)/5 & 20<x\le 25\end{cases}$$

$$u_5(x)=\begin{cases}0 & x\le 20\\ (x-20)/5 & 20<x\le 25\\ 1 & x>25\end{cases}$$

Similarly the membership function of electromagnetic radiation (x2), anchor stress (x3) and roof separation (x4) can be obtained. After the membership function of evaluation indexes are established, the test samples in Table 3 are evaluated. For example, the fuzzy relation matrix of the first sample is obtained by the above membership function, which is as follows:

$$R=\begin{bmatrix}1.0 & 0 & 0 & 0 & 0\\ 0.9 & 0.1 & 0 & 0 & 0\\ 1.0 & 0 & 0 & 0 & 0\\ 1.0 & 0 & 0 & 0 & 0\end{bmatrix}$$

Similarly, the fuzzy relationship matrix of 20 samples in the test sample set can be established

- **Determine the weight of fuzzy evaluation indexes:** It is the key problem that reasonably determined the weight of evaluation indexes for fuzzy evaluation in practical application. Because the influence degree of each evaluation index is different for mine pressure safety state, each index is given different weights. The weights are calculated by Eq. 7 in this study. Firstly, the average value of each evaluation index is calculated in test sample set

$$A = [0.6780, 22.7600, 1.5460, 15.8190]$$

The weight vector is obtained by Eq. 5 and 6:

$$W = [0.6780, 0.6503, 0.1940, 0.6591]$$

The weight vector is normalized by Eq. 7:

$$W = [0.2917, 0.2798, 0.0835, 0.2836]$$

- The weight W of evaluation indexes and fuzzy relationship matrix R are composed by fuzzy composite operator shown in Eq. 8 and fuzzy comprehensive evaluation results of each test sample is obtained

For example, the fuzzy comprehensive evaluation result vector of the first test sample is obtained:

$$Y = W\odot R = (0.8980, 0.1020, 0, 0, 0)$$

Similarly the fuzzy comprehensive evaluation result vector of other test samples can be obtained in Table 6

The grade of the sample is the biggest membership grade after grade membership of each sample is sorted. Evaluation can be made from Table 4: The safety grade of samples 1~4 is grade I, the safety grade of samples 5~8 and sample 10 is grade II, the safety grade of samples 9 and sample 12~13 is grade III, the safety grade of samples 13~16, sample 18 and sample 20 is grade IV, the safety grade of samples 17 and sample 19 is grade V. Compared with the original evaluation results given in Table 3, the evaluation results of sample 9, 18, 20 are different and the evaluation accuracy is 85%. Carefully observe, it can be found that only sample 9 is different among 16 samples which original grade is grade I~IV and the evaluation accuracy is 93.5%. Because the evaluation standard of samples which safety grade is grade V is obtained by the arithmetic sequence of previous four grades, evaluation error of the samples is more. The evaluation standard and the actual evaluation standard of coal mine pressure safety evaluation may have large discrepancy; therefore it may cause large error for evaluation of the samples which safety grade is grade V

CONCLUSION

The fuzzy is existed between safety grades of mine pressure. Dynamic fuzzy theory is used to evaluate safety state of mine pressure in the study. For the deficiency that weight is determined by expert knowledge in fuzzy evaluation, the weight of evaluation index is dynamically set according to influence degree of evaluation index on mine pressure state in the study. Through analyzing pressure monitoring data collected from coal mine in Beijing Coal Group, the accuracy is 85% using the method proposed in the study for evaluation of mine pressure safety. Because the evaluation standard of samples which safety grade is grade V is obtained by the arithmetic sequence of previous four grades, evaluation error of the samples is more. The evaluation standard and the actual evaluation standard of coal mine pressure safety evaluation may have large discrepancy; therefore it may cause large error for evaluation of the samples which safety grade is grade V. For the defect that the parameters need to be set manually in fuzzy evaluation, it is a further research problem that how to determine the evaluation standard of grade V in the study.

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