Safety evaluation of coal mine internal fire based on the neutral reference value

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Abstract: To improve the accuracy of emergency warnings of coal mine internal fire, a new coal mine internal fire safety evaluation method combining AHP with objective, neutral reference was put forward. According to the mechanism of internal fire, an evaluation index system and an evaluation hierarchy model were established, and a percentage scoring rule was set to score the underlying influencing factors. The lower the score, the greater the risk of internal fire. Combining the score of a single item with the weight of a single item, the overall score of coal mine internal fire in different periods was obtained, and the risk degree of coal mine internal fire was quantitatively expressed.

1. Introduction

The safety evaluation and analysis of various factors inducing fire accidents were obtained. Scholars used many methods to evaluate the safety of internal fires in coal mines [1-5]. According to the results, taking targeted corrective measures can forecast spontaneous coal combustion and effectively prevent fire development. However, the model established by the existing evaluation methods is complicated, leading to a huge workload. At the same time, the constructed evaluation system is generally subjective. It's difficult to make an intuitive ranking of the importance of the evaluation objects. Based on the above problems, this paper put forward the analytic hierarchy process (AHP) based on the neutral reference value. This method added the concept of neutral reference value based on AHP. It reflected the degree of influence of a single evaluated factor and a neutral reference object on a certain index. The evaluation process of this method has a small workload and obvious comparison results and is not subject to human intervention.

2. AHP based on the neutral reference object

The coal mine's internal fire safety risk assessment process is shown in Figure 1:

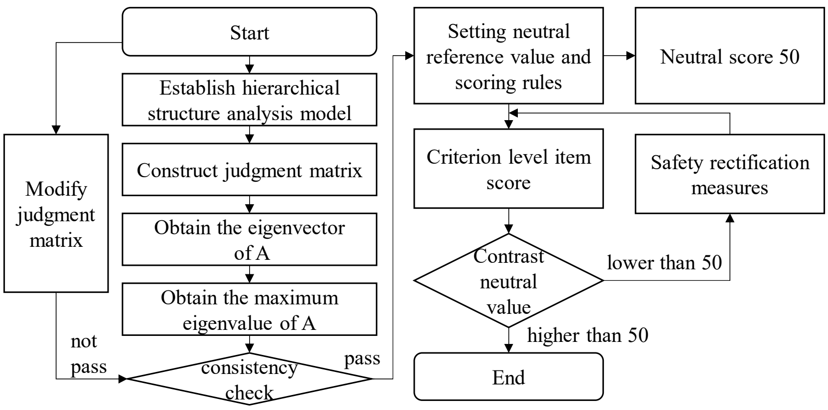

Fig. 1 Evaluation process

(1) We establish an analytic hierarchy process structure model

According to different attributes, each element related to the problem was decomposed from top to bottom into the target layer, criterion layer, and evaluation object layer.

(2) We construct a pairwise comparison judgment matrix

The judgment matrix was used to express the relative

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importance of an element at the previous level and related elements at this level to form a judgment matrix. The relative importance of each element in the evaluation object layer was obtained based on custom rules.

(3) Single-level sorting and consistency test

According to the judgment matrix, the relative importance weight of an element in a certain layer relative to an element in the previous layer was calculated. The characteristic root method was used to derive the relative ranking weight from the judgment matrix of pairwise comparison between elements. The steps were as follows:

① We calculate the maximum characteristic root of the judgment matrix λ_{max}.

② We calculate consistency index *CI*.

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{1}$$

where *n* is the order of the judgment matrix.

③ We look up the average random consistency index value table to get the corresponding average random consistency index *RI*.

④ We calculate the consistency ratio *CR*

$$CR = \frac{CI}{RI} \tag{2}$$

⑤ Consistency check

When $CR < 0.1$, it is considered that the constructed judgment matrix has satisfactory consistency; When $CR \geq 0.1$, it is considered that the judgment matrix does not have satisfactory consistency, and the judgment matrix needs to be revised.

(4) We set user-defined rules for indicator scoring

For the continuously changing quantitative index *c*, the score *s* corresponding to some values of *c* can be preset according to the actual situation. The possible values of *c* are divided into intervals, and the score corresponding to each interval boundary is given. The score can be calculated according to the linear interpolation method for the index value falling in a certain interval.

The bigger *s* is, the safer it is. When s=0, it is in an extremely unsafe situation; When s=100, it is in a very safe situation. As the neutral reference value is an evaluation index in a critical state, its index score should be 50 points.

For discrete quantitative or non-quantitative indicators, list all possible values and give them corresponding weights.

(5) We calculate each index score of the evaluated factors

We calculate each evaluated factor’s relative importance and weight value to the top-level target. When the overall score exceeds 50, it can be considered that the possibility of internal fire in the coal mine is low, and it is in a safe state. If the score is below 50, it proves that the risk of coal mine internal combustion fire is high, and safety rectification measures should be taken in time.

3. Evaluation system construction

Coal mine internal fire can be divided into three processes: incubation period, self-heating period, and combustion period. Establishing an evaluation system for the three periods and selecting different evaluation factors is necessary.

3.1 Influencing factors of the incubation period and scoring rules

The evaluation indexes and scoring rules of internal fire in coal mines during the incubation period are shown in Table 1.

Table 1 Evaluation indexes and scoring rules of internal fire in the latent period

Evaluation indexes	Neutral value	Reference value	↔	Score	Explanation
Spontaneous combustion tendency	null	I II III	↔ ↔ ↔	10 40 70	I correspond to easy to combust spontaneously. II corresponds to can combust spontaneously. III corresponds to hard to combust spontaneously.
Spontaneous combustion period	6	1 3 6 12 24	↔ ↔ ↔ ↔ ↔	10 20 50 75 90	The spontaneous combustion period of a coal seam in a China coal mine varies from 1 to 12 months.
Megaton ignition rate	null	4 3 2 1 0	↔ ↔ ↔ ↔ ↔	0 20 30 40 60	The number of internal fires per 1 million tons of coal produced in recent 10 years.
The dip angle of coal seam	12	45 12 0	↔ ↔ ↔	10 50 90	The greater the dip angle of the coal seam, the more spontaneous combustion times.
Coal seam thickness	2.5	5 2.5 0.5	↔ ↔ ↔	10 50 90	The greater the thickness of the coal seam, the more spontaneous combustion times. If multiple coal seams are mined in the coal mine, this score is the minimum of all coal seams.
Geological structure	medium	complex medium sample	↔ ↔ ↔	25 50 75	According to the complexity of mines’ geological structure, it is classified.

Mine gas grade	null	coal and outburst high gas content low gas content	↔ 25 ↔ 50 ↔ 75	Gas extraction will increase the risk of spontaneous coal combustion.
Coal mining technology	null	informal coal mining gun mining general mining fully mechanized top coal caving mining	↔ 40 ↔ 10 ↔ 30 ↔ 70	When fully mechanized top-coal caving mining, the recovery rate is often low and the risk of spontaneous combustion is high. If there are multiple mining faces in the coal mine, this score is the minimum score of all mining faces.
Goaf treatment method	null	total caving method roof slow sinking method knife column method local filling method full filling method	↔ 25 ↔ 25 ↔ 25 ↔ 70 ↔ 90	During mining, the residual coal in the goaf is sealed, which is very beneficial to prevent spontaneous combustion in the goaf. If there are multiple mining faces in the coal mine, this score is the minimum score of all mining faces.
The wind pressure difference between the upper and lower mining face	200	300 200 100	↔ 10 ↔ 50 ↔ 90	The wind pressure difference between the upper and lower mining faces should be at most 200 Pa. If there are multiple mining faces in the coal mine, this score is the minimum score of all mining faces.
Rough evaluation of measure effectiveness	medium	bad medium good	↔ 10 ↔ 50 ↔ 90	According to experience, the effect of fire prevention and extinguishing measures used in mines should be roughly evaluated.

3.2 Influencing factors of the incubation period and scoring rules

After spontaneous coal combustion enters the self-heating stage, the ratio of carbon monoxide (I_{CO}) is an index to judge the spontaneous combustion stage of coal. Different coal mines have different critical indexes when predicting internal fire in coal mines according to the ICO ratio. In general, if the I_{CO}) keeps rising and exceeds 0.45%, it indicates that the self-heating phenomenon occurs in the mine.

$$I_{\mathrm{CO}} = \frac{100C_{\mathrm{CO}}}{\Delta C_{\mathrm{O_2}}} = \frac{100C_{\mathrm{CO}}}{0.265C_{\mathrm{N_2}} - C_{\mathrm{O_2}}} \tag{3}$$

Table 2 Evaluation index and scoring rules of mine natural fire in self-heating period

Evaluation indexes	Neutral value	Reference value ↔ Score	Explanation
I_{CO}	Critical value	Alarm value↔10 Critical value↔50 Warning value↔90	Warning, critical, and alarm values should be determined according to their conditions.

3.3 Influencing Factors and Scoring Rules of Burning Fire

After spontaneous coal combustion enters the combustion period, open flame, smoke, and a large amount of combustion gas are produced. At this time, fire has occurred underground through human perception, tube bundle detection system, and fire monitoring system, the score of this period should be directly set to 0, so there is no need to select evaluation factors.

The overall internal fire scoring rules were summarized after scoring for the above three periods respectively: If it is in the combustion period (existing visible fire), the fire risk score is 0; if it is in the self-heating period (I_{CO} reaches the critical value), the fire risk score is 0.5 *Sz* (score of the self-heating period); If it is in the incubation period, the fire risk score is 50+0.5 *Sq* (score of incubation period).

4. Evaluation example

4.1 Calculating weight vectors

We constructed criterion layer judgment matrix *A*, coal flammability sub-criterion layer judgment matrix *B*, coal seam occurrence state sub-criterion layer judgment matrix *C,* and mining technology sub-criterion layer judgment matrix *D* as follows:

$$A = \begin{bmatrix} 1 & 3 & 2 & 1 \\ 1/3 & 1 & 1/2 & 1/3 \\ 1/2 & 2 & 1 & 1/2 \\ 1 & 3 & 2 & 1 \end{bmatrix}, B = \begin{bmatrix} 1 & 1 & 1/2 \\ 1 & 1 & 1/2 \\ 2 & 2 & 1 \end{bmatrix},$$

$$C = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}, D = \begin{bmatrix} 1 & 2 & 2 \\ 1/2 & 1 & 1 \\ 1/2 & 1 & 1 \end{bmatrix}$$

According to these judgment matrices, the weight vectors of each layer element can be obtained by calculating:

$$w_A = [0.3512, 0.1089, 0.1887, 0.3512]^T,$$

$$w_C = [0.25, 0.25.0.5]^T,$$

$$w_B = [0.25, 0.25, 0.25, 0.25]^T,$$

$$w_D = [0.5, 0.25, 0.25]^T$$

According to the weights vector, it can be obtained that flammability and coal mine fire prevention and extinguishing measures in the incubation period were the highest weight evaluation factors.

4.2 Self-heating period evaluation score

We counted the CO, N_2, and O_2 concentrations in a coal mining face within 20 h and calculated the I_{CO}, got the corresponding scores of CO ratio in each period, as shown in Figure 2:

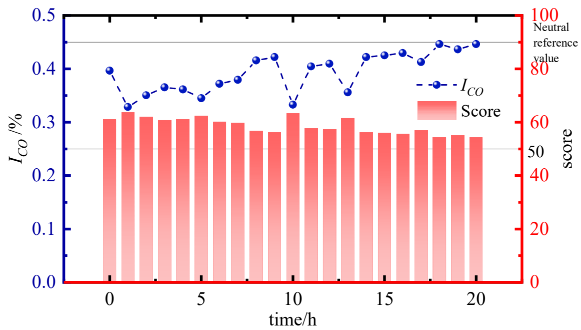

Fig. 2 Monitoring chart of I_{CO} ratio score

As can be seen from Figure 4, the scores of I_{CO} in 20 hours were all higher than 50, but I_{CO} was gradually increasing and close to the neutral reference value. If the coal temperature continues to rise and the I_{CO} is higher than the critical value, measures should be taken to prevent internal fire in time.

4.3 Incubation period evaluation score

The coal seam mined in this coal mine had low volatile content and high-water content but high brittleness, easy breakage, and certain gas content. Therefore, the grade of spontaneous combustion tendency was II, with a score of 40 points. The spontaneous combustion period was 6 months, and the score was 50. The ignition rate per million tons was 1 time, and the score was 40 points.

The coal seam thickness was 1.5 m, and the score was 70 points. The dip angle of the coal seam was 14°, which belongs to the gently inclined coal seam, and the score was 47.6 points. This coal seam was a low gas mine with a simple geological structure; the score of geological structure and mine gas content was 75 points. According to the weight of each criterion layer factor of coal seam occurrence, the overall score of the coal seam occurrence project was 66.9 points.

The score for coal mining technology was 70 points. The goaf treatment method was 70 points, and the wind pressure difference between the upper and lower mining face was 78 points. According to the weight calculation of each criterion layer factor of coal mining technology, the overall score of the mining technology project was 72 points.

According to the coal mine fire prevention measures and safety management measures, the score of fire prevention measures was 50 points. In conclusion, the overall score *Sq* of fire risk assessment in the incubation period of the mine was 53.4 points.

The overall fire risk score S= 50+0.5 Sq=76.7, higher than 75 points, which indicated that the risk of internal fire in this mine was low and less threatened by internal fire hazards in coal mines.

5. Conclusions

According to the mechanism of internal fire in the coal mine, the evaluation factors of spontaneous coal combustion in each period are selected: the evaluation factors of the incubation period are divided into coal flammability, coal seam occurrence, mining technology, and fire prevention measures. And the evaluation factor of the self-heating period is I_{CO}. According to the evaluation factors of the incubation period, the hierarchical structure model is constructed, the influence degree of each factor on internal fire risk is compared pairwise, and the judgment matrix is constructed. The consistency ratio of the judgment matrix meets the requirements, and the established evaluation model has sufficient reliability and accuracy. The score of the I_{CO} index shows that the evaluated coal mine is still in the incubation period. It shows that the possibility of internal fire in this mine is small. However, the scores of high-weight items of flammability and fire prevention and extinguishing measures are all lower than 50, which indicates that the coal in this mine can spontaneously ignite, and the fire prevention and extinguishing measures could be better. There is still the risk of internal fire. Therefore, the coal mine should strengthen the fire prevention work while improving the exploitation technology.

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