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A Study of Risk Evaluation and Early Warning Model Based on Grey System Theory

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Abstract: By introducing the theory of system safety science, and applying the gray theory prediction method, this paper aims at analysing the major hazards of spontaneous combustion of coal, and divided the impact indicators system into three categories, namely; static indicator, dynamic indicator, and intensive monitoring indicator. The static class indicator determined the hazard class by using risk evaluation, and obtained the inherent hazard class of hazard source. The dynamic class indicator serves as a real-time monitoring item. After analysing the monitoring result by the gray theory prediction, both the monitoring result and inherent hazard class were jointly integrated into the initial hazard class. After the initial hazard class was amended by intensive monitoring indicator, it became possible to obtain the ultimate hazard class corresponding to the major hazards of spontaneous combustion of coal. In the early warning of Coal Mine Gas and the major hazard of fire disaster, it was proposed to adopt the combination of dynamic and static early warning method. In essence, the static early warning serves as a kind of "early warning" for the current state of early warning indicator, while the dynamic early warning serves as the predictive judgment about the current state of early warning indicator, based on the analysis of the development trends.

Keywords: Gray system theory, risk evaluation, risk warning model.

1. INTRODUCTION

For the coal mine gas explosion and spontaneous fire risk evaluation, the system safety methods and theories were employed, and assessed by using index evaluation method [1]. The index evaluation method, also called as scoring method, is a scientific, reasonable and easy-to-operate safety evaluation method. When evaluation is made by using the index method, it is required to firstly compile the evaluation index system used for the hazard evaluation table, and secondly score the hazard evaluation table. Following this, the hazard scores are calculated by using the determined mathematical formulas (addition scoring formula, weighted scoring formula or other scoring formulas), and the hazard class is determined. This system, first of all, aimed at analyzing coal mine gas explosion and spontaneous combustion fire disaster, and compiling the risk evaluation index system for corresponding location (including the risk evaluation index system for coalface and the risk evaluation index system for excavation working face). Then, it was used to make evaluation according to the evaluation table formed by these hazard indexes, applying the index evaluation method, and respectively conducting inspection and evaluation of the evaluation indicator for gas explosion and spontaneous fire accident. Finally, the evaluation results were classified according to the risk classification criteria, and the system hazard class was obtained.

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2. MAJOR HAZARD IDENTIFICATION INDEX SYSTEM FOR COAL'S SPONTANEOUS COMBUSTION FIRE

Corresponding to the identification and early warning indicator system for the major hazards of coal mine gas emission and gas explosion as stated in the previous chapter, the indicator system used for the identification of major hazard in coal's spontaneous combustion is also divided into three components, *i.e.* static class indicator, dynamic class indicator, and intensive monitoring indicator. The difference is that the independent design of working face types is no longer different in this indicator system. Instead, a group of universal indicator systems was compiled, as shown in Table **1**.

3. INHERENT RISK EVALUATION OF FIRE ACCIDENT IN COAL'S SPONTANEOUS COMBUSTION

3.1. Inherent Risk Evaluation Table of Coal's Spontaneous Combustion Fire Accident

The inherent risk index of fire accident in spontaneous combustion of coal refers to the spontaneous combustion risk that inherently exists in coal under certain geological conditions. Therefore, the contents of this table only include the static class indicator of the index system [2]. The contents of this evaluation table are shown in Table **2**.

The weights in this evaluation table express the degree of influence of various indicators on the inherent risk of spontaneous combustion coal fire accident [3]. Due to the fact that there is no direct comparability among the influence degree of above-mentioned static evaluation indicators, it is

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Table 1. Indicators of coal spontaneous combustion fire accident.

No.	Static	Dynamic	Intensive Monitoring
1	Coal-seam thickness	CO concentration	Fire area found in adjacent layers (raise the hazard class to Level I at the occurrence of fire)
2	Dip angle of coal seam		Spontaneous combustion indicator gas (raise the hazard class to the highest when ethylene is detected)
3	Spontaneous combustion tendency of coal		Close to the fault structure band(raise the hazard class to Level I at the occurrence of this scenario)
4	The shortest combustion Period		Conveyance of coal mining face (raise the hazard class to Level I at the occurrence of this scenario)
5	The historical combustion Period		
6	Thickness of residual coal		

Table 2. Inherent risk evaluation table of coal's spontaneous combustion fire accident.

No.	Index	Contents to be Checked	Weight	Test Results	Remarks
1	Coal-seam thickness	A. Below the medium layer B. Thick coal seam C. Special thick seam	0.099		
2	Dip angle of coal seam	A. Gently inclined coal seam B. Inclined seam C. Half-edge coal seam	0.095		
3	Spontaneous combustion tendency of coal	A. Not-Easy spontaneous combustion seam B. Spontaneous combustion seam C. Easy spontaneous combustion seam	0.114		
4	The shortest combustion Period	A. 6 months or more B. 3 to 6 months C. 1 to 3 months	0.212		
5	The historical combustion Period	A. No records of historical combustion B. Records of historical combustion	0.307		
6	Thickness of residual coal	A. Greater than 0.4 m B. Less than 0.4 m	0.173		

indeed a complicated issue to evaluate the determination of indicator value Q_i. The application of analytic hierarchy process (AHP) can solve this problem. First of all, it was proposed to use the Delphi method to compare each evaluation indicator, and determine the discriminant matrix used to calculate each of the evaluation indicator weight, and obtain the weight of each evaluation indicator by using the analytic hierarchy process (AHP).

3.2. Inherent Risk Index of Fire Accident in Spontaneous Combustion of Coal

After the inherent risk evaluation, table of fire accident in spontaneous combustion of coal was compiled. It was used to conduct the evaluation of inherent risk during the initial stage of production at appropriate workplace. It required relevant personnel to fill the evaluation table according to the actual situation, and use the index evaluation method to conduct the analysis and calculation of the evaluation results. The formula of index evaluation method is as shown in equation 1.

$$F_f = \sum_{i=1}^{6} Q_i F_i \tag{1}$$

wherein F_f ——Inherent risk index of fire accident in spontaneous combustion of coal fire accident

Q_i ——Weight of static evaluation indicator i

Table 3. Scoring criterion for special risk evaluation of accident.

Test results	A	B	C
Score F_i	1	3	5

Table 4. Criteria for the classification of inherent risk class ofspontaneous combustion of coal fire accident.

Inherent Risk Class	□	□
Inherent risk index	$F_f < 3.0$	$F_f \geq 3.0$
Significance of evaluation	Safe	Risk

Table 5. Acceptable coverage table.

n	Acceptable Coverage	*n*	Acceptable Coverage
1	\	8	0.8007~1.2488
2	\	9	0.8187~1.2214
3	\	10	0.8338~1.2214
4	0.6703~1.4918	11	0.8465~1.1814
5	0.7165~1.3956	12	0.8574~1.1663
6	0.7515~1.3307	13	\
7	0.7788~1.2840	14	\

F_i ——Score of static evaluation indicator i

When special risk evaluation of fire accident in spontaneous combustion of coal was conducted, each evaluation indicator i was analyzed which corresponded to the different test results in the evaluation table of fire accident in spontaneous combustion of coal. The scoring criteria are as shown in Table **3**.

3.3. Inherent Risk Class of Fire Accident in spontaneous combustion of coal

After the inherent risk index F_f of fire accident in spontaneous combustion of coal was obtained *via* above calculation, the inherent risk class of fire accident in spontaneous combustion of coal was determined according to the inherent risk index. The risk class was divided into three classes, and the specific criteria are as shown in Table **4**.

4. PREDICTION BASED ON GRAY SYSTEM THEORY

The gray system theory, proposed by Chinese scholar Professor Deng Julong, in 1982, is based on the uncertain system characterized by “some data know”, “some data unknown”, "Small sample" and "poor data" as the object of study. The gray prediction theory provides a reliable prediction method for prediction ` in various engineering fields, and the method is listed as follows [4].

(1) Model validation

Practically, only those sequences which meet specific criteria can be predicted by applying GM (1, 1) gray prediction model. For this reason, it is necessary to validate the sequence to be predicted, and this method is called as class ratio test.

Suppose $X^{(0)} = \left\{x^{(0)}(1), x^{(0)}(2), x^{(0)}(3), \ldots x^{(0)}(n)\right\}$ as the original sequence, and its class ratio shall be:

$$\sigma(k) = \frac{x^{(0)}(k-1)}{x^{(0)}(k)}, k = 1,2,3,\ldots,n \quad (2)$$

The class ratio shall be configured as:

$$\sigma = (\sigma^{(0)}(2), \sigma^{(0)}(3),\ \sigma^{(0)}(\mathrm{n})) \quad (3)$$

Table **5** was analyzed to check whether the class ratio can fall within the acceptable coverage. This model can be used to conduct the test, only when the class ratio falls within this coverage.

(2) Data transformation

If the sequence fails to pass the class ratio test, it is required to conduct the data transformation process is followed. The gray prediction can be conducted using GM (1,1) model, under the premise that the class ratio of sequence after data transformation falls within the acceptance coverage table.

Table 6. Risk class determination of dynamic indicators.

No.	Risk Class		
	I	II	III
CO concentration	Concentration of less than 24ppm	Concentration on the rise, yet still lower than 24ppm	Concentration on the rise, and exceeds 24ppm

(3) Model establishment

The white type formula of GM (1,1) model shall be,

$$\begin{cases} \hat{x}^{(1)}(k) = (x^{(0)}(1) - \dfrac{b}{a})e^{-a(k-1)} + \dfrac{b}{a} \\ \hat{x}^{(0)}(k) = \hat{x}^{(1)}(k) - \hat{x}^{(1)}(k-1) \end{cases} \tag{4}$$

A. Calculate AGO sequence of $x^{(0)}$

$$x^{(1)}(k) = \sum_{i=1}^{k} x^{(o)}(i) \tag{5}$$

B. Calculate the mean value sequence of $x^{(1)}$

$$z^{(1)}(k) = 0.5(x^{(1)}(k) + x^{(1)}(k-1)) \tag{6}$$

C. Calculate the model parameter

$$\begin{cases} a = \dfrac{CD - (n-1)E}{(n-1)F - C^2} \\ b = \dfrac{DF - CE}{(n-1)F - C^2} \end{cases} \tag{7}$$

Wherein $C = \sum_{k=2}^{n} z^{(1)}(k)$, $D = \sum_{k=2}^{n} x^{(0)}(k)$

$$E = \sum_{k=2}^{n} (z^{(1)}(k)x^{(0)}(k)),\ F = \sum_{k=2}^{n} (z^{(1)}(k))^2$$

(4) Accuracy test

Applying GM (1,1) prediction model to conduct the test of prediction accuracy, and using the residual error test method. The test formula is as shown below.

Residual error:

$$\xi(k) = \frac{x^{(0)}(k) - \hat{x}^{(0)}(k)}{x^{(0)}(k)} \times 100\% \tag{8}$$

Mean residual error:

$$\xi(avg) = \frac{\sum_{k=2}^{n} |\xi(k)|}{n-1} \times 100\% \tag{9}$$

General requirement is $\xi(avg) < 20\%$, and it is best to ensure $\xi(avg) < 10\%$.

(5) Data prediction

By substituting the original data sequence into GM (1,1) forecasting model and carrying out mathematical operation, it is possible to obtain the corresponding projection data

4.2. Determination of Risk Class of Fire Accident in spontaneous combustion of coal

The real-time monitoring data curve can be obtained if dynamic indicators are monitored on real-time basis. The trend curve of dynamic indicators can be obtained after the above algorithm is applied to predict the dynamic indicators and obtain the predicted data. The risk class of predicted data can be obtained after the analysis of curve characteristic. The criterion rule for risk class determination is as shown in Table **6**.

The initial risk class of fire accident in spontaneous combustion of coal can be obtained by combining the inherent risk class of fire accident coal's spontaneous combustion and the risk class of dynamic indicators. Following this, the intensive indicators are analyzed having impact on the risk of fire accident in coal's spontaneous combustion [5], and the amendments are made to the initial risk class, and to ultimately obtain the risk class of fire accident in spontaneous combustion of coal .

5. MAJOR HAZARD WARNING OF FIRE ACCIDENT COAL'S SPONTANEOUS COMBUSTION

According to the above steps, it is possible to finalize the grey prediction & analysis of the dynamic indicators in spontaneous combustion of coal fire accident, and conduct risk class determination [6]. In response to the respective characteristics of above warning contents, the major hazard identification and early warning method has been designed for analyzing fire accident in spontaneous combustion of coal . The warning method, on one hand, comprises of the static early warning that integrates the analysis of current state, and on the other hand, also comprises of the dynamic early warning that integrates the prediction & analysis of future state. The static early warning and dynamic early warning operates independently and simultaneously. The early warning results jointly constitute the conclusion of major hazard identification and early warning technology of fire accident in spontaneous combustion of coal. Early warning data is discussed below.

5.1. Static Early Warning

The static early warning serves as the "warning" of the current state of early warning indicators. After the monitoring value of monitoring indicators is obtained, the risk class is determined corresponding to the values, to provide static

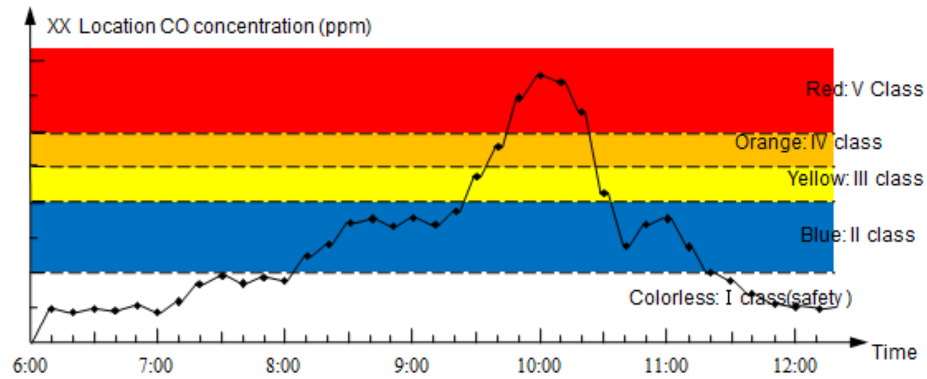

Fig. (1). Example of dynamic early warning trend diagram.

Table 7. The rule for dynamic early warning.

No.	Basic Value	Trend	Changes In Risk Class	Early Warning Prompt
1	$A \in$ Ⅰ	□	No	Safe
2	$A \in$ Ⅰ	→	No	Safe
3	$A \in$ Ⅰ	□	Remain to be lifted	Index value on the rise, risk class not yet raised
4	$A \in$ Ⅰ	□	Already lifted, and keep on rise	Risk class will be raised X class at X time
5	$A \in$ Ⅱ,Ⅲ,Ⅳ,Ⅴ	□	Remain to be lowered	Index value lowered, yet, the risk class not yet lowered
6	$A \in$ Ⅱ,Ⅲ,Ⅳ,Ⅴ	□	Already lowered, not reached the safe state	Risk class will be lowered to X class at X time, not yet reached the safe state
7	$A \in$ Ⅱ,Ⅲ,Ⅳ,Ⅴ	□	Already lowered, reached the safe state	Risk class will be lowered to safety class at X time
8	$A \in$ Ⅱ,Ⅲ,Ⅳ,Ⅴ	→	No	Risk class at X class
9	$A \in$ Ⅱ,Ⅲ,Ⅳ,Ⅴ	□	Remain to be lifted	Risk class is in X class, and presents the upward trend
10	$A \in$ Ⅱ,Ⅲ,Ⅳ,Ⅴ	□	Already lifted, and keep on rise	Risk class is in X class, and keeps on rise: to be raised to X class at X time

early warning according to the risk class. In this way, , early warning is generated for the current dangerous state using early warning indicators.

The single application of static early warning can not meet the daily needs of mine safety work. In practice, it is still required to achieve dynamic predication and dynamic early warning of the risk of fire accident in spontaneous combustion of coal, according to the early warning indicators (dynamic class indicators) along the application of prediction & analysis method of analysis [7]. As a result, more accurate basis can be provided for the release of early warning information.

5.2. Dynamic Early Warning

The dynamic early warning proposed to predict the state that may occur in the future, through the determination of the changes in the risk class of early warning indictors during a period of time [8], and provide the warning in advance according to the prediction result, so as to avoid the occurrence of this potential risk.

5.2.1. Tendency Diagram of Dynamic Early Warning

The dynamic warning method used for the identification of major hazard and the early warning technology of fire accident in spontaneous combustion of coal are based on the gray theory of "Trend early warning method" [9]. This method used the dynamic indicators monitoring and forecasting data to draw the diagram of time sequence trend curve, with the purpose of analyzing the development trends to predict the potential risk and class, and make further warning regarding the release of the early warning information. The trend diagram is shown in Fig. (**1**).

Through the analysis of the above diagram, it can be observed that this simple & intuitive trend-based dynamic warning method facilitates the real-time monitoring of the risk of fire accident in spontaneous combustion of coal , in order to develop relevant preventive measures, and control or reduce the risk.

5.2.2. The Rule for Dynamic Early Warning

The core of dynamic early warning aims to correctly predict the development trend of indicators and issue appropriate warning information. It was used to predict and analyze the trend in the diagram and selected value of future time, and develop the "rule for dynamic early warning" to realize this core function. [10]

In this rule, the basic value A serves as the current value of early warning indicator（$\hat{y}\big|_{x=0}$） . According to the slope of regression equation, the development trend can be divided into three scenarios, *i.e.* Rise (↗), keep (→), and decrease (↘). The changes in risk class are referred to the values of $\hat{y}\big|_{x=4}$, $\hat{y}\big|_{x=8}$ 和 $\hat{y}\big|_{x=24}$, and the corresponding value is selected. Depending on the different scenarios combined with three factors, the rule provides a corresponding early warning promptly. The specific contents of dynamic early warning rule are shown in Table **7**.

CONCLUSION

(1) The inherent risk of fire accident in spontaneous combustion of coal can be determined by evaluating the static indicators through the application of index method. The risk class of dynamic indicators can be obtained by processing and analyzing dynamic indictors through the application of gray theory prediction algorithm. The initial risk class of fire accident being the major hazard in spontaneous combustion of coal can be obtained by combining the inherent risk class in determination. The study analyzed and considered the state of intensive monitoring indicators, made amendment to the initial risk class, and subsequently obtained the final risk class.

(2) The early warning method comprises of the dynamic early warning and static early warning. The former refers to the warning when the early warning indicator of risk class is achieved , while the latter analyzes and processes the results through the application of dynamic early warning rule. (3) The simple, intuitive and trend-based dynamic early warning method facilitates the real-time monitoring of the risk of fire accident in spontaneous combustion of coal , to develop relevant preventive measures, and control or reduce the risk.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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