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A study of risk evaluation and early warning model based on grey system theory

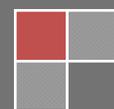
Yongchun Miao^{1*}, Jiayu Huo²¹Faculty of Resources and Safety Engineering, China University of Mining and Technology (Beijing), Beijing, 100083, (CHINA)²Poly Energies Holding Co.,LTD, 100002, (CHINA)

ABSTRACT

By starting from the theory of system safety science, and applying the gray theory prediction method, this paper aims at the major hazards of coal spontaneous combustion, and divides the impact indicators system into three categories, namely, static indicator, dynamic indicator, and intensive monitoring indicator. The static class indicator determines the hazard class by using risk evaluation, and obtains the inherent hazard class of hazard source. The dynamic class indicator serves as a real-time monitoring item. After the monitoring result is analyzed by the gray theory prediction, both the monitoring result and inherent hazard class shall be jointly integrated into the initial hazard class. After the initial hazard class is amended by intensive monitoring indicator, it is possible to obtain the ultimate hazard class corresponding to the major hazards of coal spontaneous combustion. In the early warning of Coal Mine Gas and the major hazard of fire disaster, it is 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.



For the coal mine gas explosion and spontaneous fire risk evaluation, it is proposed to apply the system safety methods and theories, and assess by using index evaluation method. 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. Next, calculate the hazard scores by using the determined mathematical formulas (Addition scoring formula, weighted scoring formula or other scoring formulas), and determine the hazard class. In this system: First of all, it is proposed to aim at coal mine gas explosion and spontaneous combustion fire disaster, and compile 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). Next, it is proposed to make evaluation according to the evaluation TABLE formed by these hazard indexes, apply the index evaluation method, and respectively make inspection & evaluation of the evaluation indicator for gas explosion and the evaluation indicator for spontaneous fire accident. Finally, it is proposed to classify the evaluation results according to the risk classification criteria, and obtain the system hazard class.

MAJOR HAZARD IDENTIFICATION INDEX SYSTEM FOR COAL SPONTANEOUS COMBUSTION FIRE

Corresponding with 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 applied in the major hazard identification of coal 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 distinguished in this indicator system. Instead, a group of universal indicator system is compiled, as shown in TABLE 1.

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		

INHERENT RISK EVALUATION OF COAL SPONTANEOUS COMBUSTION FIRE ACCIDENT

Inherent risk evaluation TABLE of coal spontaneous combustion fire accident

The inherent risk index of coal spontaneous combustion fire accident refers to the spontaneous combustion risk that inherently exists in coal under certain geological conditions. Therefore, the contents of this TABLE only comprise the static class indicator in the index system. The contents of this evaluation TABLE are as shown in TABLE 2.

TABLE 2 : Inherent risk evaluation table of coal 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		

The weights in this evaluation TABLE express the degree of influence of various indicators on the inherent risk of spontaneous combustion coal fire accident. Due to the fact that there is no direct comparability among the influence degree of above-mentioned static evaluation indicators, it is 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 is 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).^[2]

Inherent risk index of coal spontaneous combustion fire accident

After the inherent risk evaluation TABLE of coal spontaneous combustion fire accident is compiled, it is proposed to conduct its evaluation of inherent risk during the initial stage of production at appropriate workplace. Relevant personnel shall fill the evaluation TABLE according to the actual situation, and use the index evaluation method to conduct analysis and calculation of the evaluation results. The formula of index evaluation method is as shown in the formula 1.^[3]

$$F_f = \sum_{i=1}^6 Q_i F_i \quad (1)$$

Wherein: F_f — Inherent risk index of coal spontaneous combustion fire accident

Q_i — Weight of static evaluation indicator i

F_i — Score of static evaluation indicator i

When the special risk evaluation of coal spontaneous combustion fire accident is conducted, it is proposed to aim at the above each evaluation indicator i , and correspond to the different test results in the evaluation TABLE of coal spontaneous combustion fire accident. The scoring criteria are as shown in TABLE 3.

TABLE 3 : Scoring criterion for special risk evaluation of accident

Test results	A	B	C
Score F_i	1	3	5

Inherent risk class of coal spontaneous combustion fire accident

After the inherent risk index F_f of coal spontaneous combustion fire accident is obtained via the above calculation, it is proposed to determine the inherent risk class of coal spontaneous combustion fire accident according to the inherent risk index. The risk class can be divided into three, and the specific criteria are as shown in TABLE 4.

TABLE 4 : Criteria for the classification of inherent risk class of coal spontaneous combustion fire accident

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

PREDICTION BASED ON GRAY SYSTEM THEORY

The gray system theory, proposed by Chinese scholar Professor Deng Julong in 1982, takes 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 the predictive work in various engineering fields, and its use method is listed as follows,^[1]

Model validation

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

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

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

The class ratio shall be configured as:

$$\sigma = (\sigma^{(0)}(2), \sigma^{(0)}(3), \dots, \sigma^{(0)}(n)) \tag{3}$$

Apply the TABLE 5 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.

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	∖

Data transformation

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

Model establishment

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

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

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

$$x^{(1)}(k) = \sum_{i=1}^k x^{(0)}(i) \quad (5)$$

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

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

C. Calculate the model parameter

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

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

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

Accuracy test

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

Residual error:

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

Mean residual error:

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

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

Data prediction

Substitute the original data sequence into GM (1,1) forecasting model and carry out mathematical operation, it is possible to obtain the corresponding projection data.

Risk class determination of coal spontaneous combustion fire accident

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.^[4] 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.

TABLE 6 : Risk class determination of dynamic indicators

No.	Risk Class		
	CO concentration	Concentration of less than 24ppm	Concentration on the rise, yet still lower than 24ppm

The initial risk class determination of coal spontaneous combustion fire accident can be obtained by combining the inherent risk class of coal spontaneous combustion fire accident and the risk class of dynamic indicators. Next, it is proposed to analyze the intensive indicators having impact on the risk of coal spontaneous combustion fire accident, work out the determination, make amendments to the initial risk class, and ultimately obtain the risk class of coal spontaneous combustion fire accident.

MAJOR HAZARD WARNING OF COAL SPONTANEOUS COMBUSTION FIRE ACCIDENT

According to the above steps, it is possible to finalize the grey prediction & analysis of the dynamic indicators in coal spontaneous combustion fire accident, and conduct the risk class determination. In response to the respective characteristics of above warning contents, it is proposed to design the major hazard identification and early warning method for coal spontaneous combustion fire accident. The warning method, on one hand, comprises the static early warning that integrates the analysis of current state, on the other hand, also comprises the dynamic early warning that integrates the prediction & analysis of future state. The static early warning and dynamic early warning operate on independent and simultaneous basis. The early warning results jointly constitute the conclusion of major hazard identification and early warning technology of coal spontaneous combustion fire accident. That is, early warning data.

Static early warning

In fact, 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, it is proposed to determine the risk class corresponding to the values, and conduct static early warning according to the risk class. That is, early warning for the current dangerous state of early warning indicators.^[5]

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

Dynamic early warning

For the dynamic early warning, it is proposed to predict the state that may occur in the future, through the determination of the changes in the risk class of early warning indicators during a period of time, and provide the warning in advance according to the prediction result, so as to avoid the occurrence of this potential risk.^[6]

Tendency diagram of dynamic early warning

The dynamic warning method for major hazard identification and early warning technology of coal spontaneous combustion fire accident is based on the gray theory of "Trend early warning method".

That is, apply the dynamic indicators monitoring and forecasting data to draft the time sequence trend curve diagram, with the purposes of analyzing the development trends, predicting the potential risk and class, and make further warning. i.e. release of the early warning information. The example of trend diagram is as show in Figure 1.

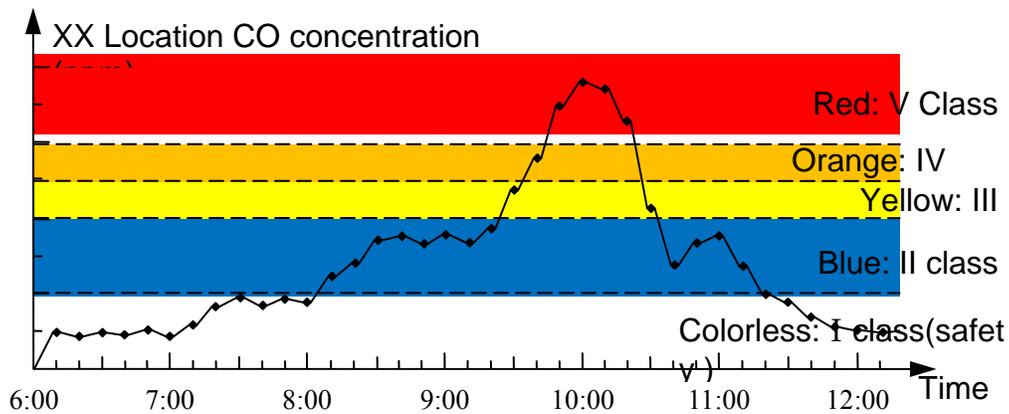


Figure 1 : Example of dynamic early warning trend diagram

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

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.^[7] It is proposed to predict & 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.

In this rule, the basic value A serves as the current value of early warning indicator ($\hat{y}|_{x=0}$). According to the slope of regression equation, the development trend can be divided into three scenarios, i.e. Rise (\nearrow), keep (\rightarrow), and decrease (\searrow). The changes in risk class shall refer to the values of $\hat{y}|_{x=4}$, $\hat{y}|_{x=8}$ and $\hat{y}|_{x=24}$, and conduct the corresponding value selection. Depending on the different scenarios combined with three factors, the rule provides corresponding early warning prompt.^[8] The specific contents of dynamic early warning rule are as shown in TABLE 7.

TABLE 7 : The rule for dynamic early warning

No.	Basic Value	Trend	Changes in risk class	Early Warning Prompt
1	$A \notin$	\searrow	No	Safe
2	$A \notin$	\rightarrow	No	Safe
3	$A \notin$	\nearrow	Remain to be lifted	Index value on the rise, risk class not yet raised
4	$A \notin$	\nearrow	Already lifted, and keep on rise	Risk class will be raised X class at X time
5	$A \in \text{II, III, IV, V}$	\searrow	Remain to be lowered	Index value lowered, yet, the risk class not yet lowered
6	$A \in \text{II, III, IV, V}$	\searrow	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	$A \in \text{II, III, IV, V}$	\searrow	Already lowered, reached the safe state	Risk class will be lowered to safety class at X time
8	$A \in \text{II, III, IV, V}$	\rightarrow	No	Risk class at X class
9	$A \in \text{II, III, IV, V}$	\nearrow	Remain to be lifted	Risk class is in X class, and presents the upward trend
10	$A \in \text{II, III, IV, V}$	\nearrow	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

CONCLUSIONS

(1) The inherent risk of coal spontaneous combustion fire accident can be obtained by evaluating the static indicators through the application of index method. The risk class of dynamic indicators can be obtained by processing & analyzing dynamic indicators through the application of gray theory prediction algorithm. The initial risk class of major hazard of coal spontaneous combustion fire accident can be obtained by combining the inherent risk class in determination. It is proposed to analyze & consider the state of intensive monitoring indicators, make amendment to the initial risk class, and subsequently obtain the final risk class.

(2) The early warning method comprises dynamic early warning and static early warning. The former refers to the warning when the early warning indicator of risk class is reached, while the latter analyzes & 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 in coal spontaneous combustion fire accident, so as to develop relevant preventive measures, and control or reduce the risk.

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