Risk Assessment Method of Coal Spontaneous Combustion Based on Catastrophe Theory

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Abstract. Coal spontaneous combustion is one of the major threats to coal production in China. It is very important to quote scientific and effective evaluation in order to prevent coal spontaneous combustion effectively. This paper use catastrophe theory to study the risk assessment method of coal spontaneous combustion. Used analytic hierarchy process (AHP) to determine the weight of 16 indicators to establish an evaluation model which based on catastrophe theory. Analyzed the catastrophe level value of coal spontaneous combustion hazard obtained by the catastrophe theory calculation method to determine the hazard level, and put forward corresponding suggestions. Through engineering case studies, the feasibility and effectiveness of the coal spontaneous combustion risk assessment method proposed in this paper is verified.

Keywords: Coal; Spontaneous combustion; AHP; Evaluation index; Model; Catastrophe theory.

1. Introduction

According to statistics, more than 90% of coal fire accidents in China are caused by spontaneous combustion of coal seams[1]. In order to realize coal safety production, it is very important and basic to evaluate the risk of coal spontaneous combustion. At present, there are mainly fuzzy comprehensive evaluation method [2], unknown measure evaluation method [3], safety evaluation index method [4], neural network method [5] and so on. These methods have their own characteristics and advantages, but the evaluation results are relatively general and broad.

It is very suitable to study coal spontaneous combustion with catastrophe theory, which can accurately calculate the catastrophe level value of each coal spontaneous combustion index. catastrophe evaluation method can fit uncertainty and mutation smoothly in spontaneous combustion of coal.

2. Evaluation Method of Coal Spontaneous Combustion Risk

2.1. Analytic Hierarchy Process (AHP)

AHP is a kind of decision analysis method combining qualitative and quantitative analysis, which can make the results more simple and clear.

The calculation steps are shown in Figure 1.
2.2. Evaluation Method Based on Catastrophe Theory

French mathematician Rene Thom proposed the catastrophe theory method. It is an important method for the evaluation and analysis of complex systems [6]. According to the catastrophe theory and the characteristics of coal spontaneous combustion, the catastrophe evaluation method is especially suitable for the risk assessment of coal spontaneous combustion.

When each control variable satisfies the bifurcation equation, catastrophe will occur in the research system [7]. It is necessary to derive the normalization formula by using the bifurcation equation in the form of decomposition. The normalization formula can normalize the control variables of different quality states that cannot be compared in the system to the same quality state that can be compared. After the quantitative recursive operation of the system, the function value of the system can be obtained [8]. Rene Thom found that when the state variables are one to two and the control variables are one to four, seven kinds of catastrophic model can be generated. Four of them are commonly used, namely Cusp Catastrophe, Swallowtail Catastrophe, Butterfly Catastrophe and Shed Catastrophe.

3. Establishment of Evaluation Index System of Coal Spontaneous Combustion Risk

3.1. Establishment of Coal Spontaneous Combustion Risk Evaluation Index System

According to the analysis of the previous actual accident cases and related literature [9,10], the index system of coal spontaneous combustion risk assessment is established, as shown in Figure 2.

![Figure 2. Coal spontaneous combustion risk evaluation index system](image-url)
3.2. Establishment of Catastrophic Model
Based on the above evaluation index system, a cascade catastrophe model of coal spontaneous combustion risk assessment is established, as shown in Figure 3.

![Figure 3. Cascade catastrophe model of coal spontaneous combustion risk assessment](image)

3.3. Determination of Weight
According to the basic principle of AHP and referring to the opinions of coal mine safety management experts on "one ventilation and three prevention", the weight value of each level index in Figure 2 are calculated, as shown in Table 1.

| Criterion layer | Index layer | Index layer weight | Weight of criterion layer |
|-----------------|-------------|--------------------|---------------------------|
| B1              | C1          | 0.0875             |                           |
|                 | C2          | 0.0231             | 0.1658                    |
|                 | C3          | 0.0551             |                           |
|                 | C4          | 0.1471             |                           |
| B2              | C5          | 0.0842             | 0.2634                    |
|                 | C6          | 0.0321             |                           |
|                 | C7          | 0.1961             |                           |
| B3              | C8          | 0.1122             | 0.3512                    |
|                 | C9          | 0.0428             |                           |
|                 | C10         | 0.0136             |                           |
|                 | C11         | 0.0270             |                           |
| B4              | C12         | 0.0540             | 0.1756                    |
|                 | C13         | 0.0810             |                           |
|                 | C14         | 0.0289             |                           |
| B5              | C15         | 0.0087             | 0.0439                    |
|                 | C16         | 0.0063             |                           |

It can be concluded that the importance ranking (descending order) of the three-level indicators is: {C1, C3, C2}, {C4, C5, C6}, {C7, C8, C9}, {C13, C12, C11, C10}, {C14, C15, C16}; The order of importance (descending order) of secondary indicators is: {B3, B2, B4, B1, B5}.

4. Application Example of Coal Spontaneous Combustion Risk Assessment

4.1. Mine Survey
In this paper, the southeast of Ningwu coalfield is discussed. The mineable coal seams are 2# coal seam and 5# coal seam, which are divided into four mining areas: 2# coal seam is divided into 201 and 202 mining areas, and 5# coal seam is divided into 506 and 507 mining areas. The research shows that the spontaneous combustion frequency is high.

4.2. Risk Assessment of Coal Spontaneous Combustion

4.2.1. Selection of catastrophe model and normalization of lower level indexes. Invite safety
management personnel of coal mining enterprises to evaluate. According to the average score of managers and the grades of each index, the decision matrix $X, X^T$ is constructed as follows:

$$
X = \begin{pmatrix}
0.9415 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.9904 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.9681 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.9441 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.9555 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.8990 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.9619 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.9700 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.9312 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.9300 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.8180 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.9640 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.9530 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.7783 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.7460 & 0.6 & 0.7 & 0.8 & 0.9 \\
0.9069 & 0.6 & 0.7 & 0.8 & 0.9 \\
\end{pmatrix}
$$

According to the standardized data and calculation method of catastrophic model[8][11], the normalization results are shown in table 2 below.

**Table 2. Normalization results of tertiary indexes**

| Risk factors            | Normalization of three level indexes |
|-------------------------|-------------------------------------|
| Personnel               | $x_{c1} = \sqrt{0.9415} = 0.9703, x_{c3} = \frac{\sqrt{0.9681}}{3} = 0.9892, x_{c2} = \frac{\sqrt{0.9904}}{3} = 0.9976$ |
| Technical equipment     | $x_{c4} = \sqrt{0.9441} = 0.9716, x_{c5} = \frac{\sqrt{0.9555}}{3} = 0.9849, x_{c6} = \frac{\sqrt{0.8990}}{3} = 0.9737$ |
| Fire handling           | $x_{c7} = \sqrt{0.9619} = 0.9808, x_{c8} = \frac{\sqrt{0.9700}}{3} = 0.9899, x_{c9} = \frac{\sqrt{0.9312}}{3} = 0.9823$ |
| Safety management       | $x_{c13} = \sqrt{0.9530} = 0.9762, x_{c12} = \frac{\sqrt{0.9640}}{3} = 0.9879, x_{c11} = \frac{\sqrt{0.8180}}{3} = 0.9856$ |
| Coal seam               | $x_{c14} = \sqrt{0.7783} = 0.8822, x_{c15} = \frac{\sqrt{0.7460}}{3} = 0.9069, x_{c16} = \frac{\sqrt{0.9069}}{3} = 0.9759$ |

According to the complementary relationship, the Catastrophe Progression 1 of secondary index are shown in table 3 below.

**Table 3. Catastrophe Progression 1 of secondary index**

| Risk factors            | Evaluation principle | Catastrophe level value |
|-------------------------|----------------------|-------------------------|
| Personnel               | complementary        | $B_1 = \frac{x_{c1} + x_{c2} + x_{c3}}{3} = 0.9857$ |
| Technical equipment     | complementary        | $B_2 = \frac{x_{c4} + x_{c5} + x_{c6}}{3} = 0.9767$ |
| Fire handling           | Non complementary    | $B_3 = \min\{x_{c7}, x_{c8}, x_{c9}\} = 0.9808$ |
| Safety management       | complementary        | $B_4 = \frac{x_{c10} + x_{c11} + x_{c12} + x_{c13}}{4} = 0.9752$ |
| Coal seam               | Non complementary    | $B_5 = \min\{x_{c14}, x_{c15}, x_{c16}\} = 0.8822$ |

Calculate the catastrophe progression value of the first level index, the comprehensive catastrophe count value of spontaneous combustion risk is obtained by using complementary principle.

$$
x_{b1} = \sqrt{0.9808} = 0.9903, x_{b2} = \frac{\sqrt{0.9767}}{3} = 0.9922, x_{b4} = \frac{\sqrt{0.9752}}{3} = 0.9937,
\quad x_{b1} = \frac{\sqrt{0.9857}}{3} = 0.9971, x_{b} = \frac{\sqrt{0.8822}}{3} = 0.9793
$$
4.2.2 Analysis of evaluation results. The hazard composite catastrophe progression value of spontaneous combustion risk in the mine is $A = 0.9879$. According to the risk level of the relevant indicators, the classification intervals are relatively safe. According to the investigation, the results of the evaluation method used in this paper are consistent with the actual situation, which shows that it has certain reference significance. The catastrophe progression values corresponding to the secondary indicators are as follows: $B_1 = 0.9971$, $B_2 = 0.9922$, $B_3 = 0.9903$, $B_4 = 0.9937$, $B_5 = 0.9793$. According to the risk level of the relevant indicators, the classification intervals are: relatively safe, relatively safe, general safe, relatively safe and relatively safe. The results show that personnel factors, technical equipment factors, safety management factors and coal seam factors are in a relatively safe state. Compared with the other four aspects, the safety degree of fire treatment capacity factor is the lowest, and measures should be taken in time to strengthen.

4.3. Measures and Suggestions for Improving the Safety of Spontaneous Combustion

There are still some problems in the construction of spontaneous combustion and fire prevention in this mine. The research on prevention of spontaneous combustion should be continued. In addition, to strengthen the construction of enterprise safety management, improve the safety awareness and skills of operators.

5. Conclusion

(1) A scientific and effective risk assessment model of coal spontaneous combustion is established.
(2) It is scientific and reasonable to use the AHP to calculate the weight value of the evaluation index, combined with catastrophe evaluation method, to evaluate the risk of coal spontaneous combustion.
(3) The feasibility and effectiveness of coal spontaneous combustion risk assessment method based on catastrophe theory are verified by an example. The results are in line with the actual situation of the mine.

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