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Establishment and Application of Early Warning Model for Gas Safety Management

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In order to realize the safety warning of coal mine gas content to prevent gas safety accidents, this paper combined the catastrophe theory and mathematical modeling to establish an early warning model for gas safety management, and the corresponding function change relation was deduced by fuzzy mathematics. Through further study of the variables in this function relationship and the trial in Yuwu Coal, the corresponding models were chosen to calculate the accident grade, which verified relevant theories and the feasibility of the early warning model in the gas safety management to some extent.

1. Introduction

In recent years, due to the frequent coal mine accidents, the gas safety management has become a hot issue nowadays. The real-time and accurate monitoring of gas content and related data is the basic way to realize gas safety management in the coal mine production.

This paper, mainly through the combination of the fuzzy mathematics theory, catastrophe theory, and mathematical modeling, built the early warning model for gas safety management in coal mine operations, and then discussed the feasibility of the relevant theoretical models in the gas safety management through further analysis of Yuwu Coal data.

2. Literature review

Coal has been the main source of energy for a long time. It has a relatively high proportion in the total production and consumption of primary energy. Coal will remain the main energy source in China for a long time. In recent years, the proportion of coal in the disposable energy production and consumption structure has always been around 70%. It is estimated that by 2050, it will account for more than 50%. The coal industry has played and continues to play an important role in the national economy. In recent years, the total amount of coal in China has continued to grow from 1.299 billion tons in 2000 to 2.19 billion tons in 2005. In 2010, the country's coal production reached 3.24 billion tons. In 2013, the national coal output reached 3.7 billion tons. However, it should be noted that China is also one of the countries with the most serious accidents in coal mines.

With the rapid development of network technology and the full penetration of the economy and society, on the one hand, it has had a huge positive impact on the economic and social development in the world. On the other hand, it has brought cyberspace security to avoid more threats and challenges. Cyber-attacks have become more frequent and cybercrimes have become more and more serious. This poses a certain degree of threat to national security. In this environment, fast and accurate early warning defense is very important for network security. Under the overall security policy control box, a network security defense early warning system model based on three domain network models forms a complete and dynamic security domain. It is the ability of an early warning and defense information system to implement active defense. In China and abroad, scientific research workers have conducted theoretical research and practical research on outbreak prevention technology. Through comparative analysis, an early warning system based on network technology, big data mining methods, and GIS analysis was established. The early warning research results provide a good idea for further research on dynamic early warning (Zhang et al., 2017). Jinag et al. introduced a real-

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time monitoring and warning method for surface coal and gas outburst based on the dynamic variation of stress and gas concentration-SMD method. Drilling surface coal and gas outburst monitoring and early warning systems were established. The dynamic changes of surrounding rock stress on the tunneling face and the dynamic changes of coal gas concentration were monitored. According to the monitoring results, the degree of danger of coal and gas outburst is judged. This study has important implications for the production of coal mines (Jiang et al., 2017). Based on the risk theory of triangular fuzzy numbers, a risk index system and a three-dimensional risk analysis model were constructed. This compensates for the shortcomings of the existing risk assessment methods for major hazards. Through concrete engineering cases, the validity and applicability of the models and methods built were verified (Wu et al., 2014). Taking the Luzhou kiln coal mine as an example, the influencing factors of rockburst were determined. Using the PCA method and GRNN method, a risk prediction model for rockburst was established. According to the measurement data of Yanzhou kiln, the above model was used to calculate the average forecast error. The results show that the model is superior in terms of approximating ability and learning speed (Shi et al., 2014). The dynamic clustering algorithm was used to effectively divide the gas concentration monitoring data. Using the DE algorithm, dynamic clustering algorithm and Gaussian regression, a gas concentration interval prediction model was established. The comparative analysis method was used to prove the rationality of the model (Sajjadi, 2015). Scholars pointed out problems in the process of gas explosion. From the aspects of man, machine, ring, and pipe, the factors influencing gas explosion in coal mines are analyzed. The coal mine gas explosion disaster situation assessment index system and ANP-SPA assessment model were established (Qin et al., 2016).

The concept of data mining is introduced to solve the problems such as the low ability of comprehensive data analysis and processing of coal mine safety monitoring systems and the inability of abnormal gas anomalies to be identified. The core algorithm algorithms and FP-growth algorithms for Apriori data mining correlation analysis are analyzed. A correlation analysis model for coal mine gas monitoring data was designed. The model is based on the above two algorithms. By using the cloud model to convert from continuous data to qualitative data, valuable association rules are then mined from the monitoring data. Finally, an experimental analysis of coal mine gas monitoring data was conducted. This method has a certain guiding role in improving coal mine gas safety monitoring and early warning capabilities (Liaw, 2016). Darnell et al. found that the Marcellus shale formation contains a lot of natural gas reserves, which are increasingly extracted using horizontal drilling techniques. Concerns about environmental impacts have led to research on the operation of Mars, including the safety of pits and reservoirs containing fracturing fluids and fresh water. A subset of these structures in West Virginia are evaluated using risk-based field data collection tools. This tool reveals frequently occurring problems. A probability based approach is developed to determine the probability of occurrence of these problems under larger sample sizes. The combination of this method in pits and reservoirs will benefit the industry by identifying areas for improvement in construction and inspection (Darnell et al., 2016).

To sum up, coal mine safety early warning is a complex systematic project. The above research has been systematically studied from the classification and identification methods of hazard sources, the establishment of evaluation index system, the evaluation model based on various theories and the economic benefits of safety input, and a series of achievements have been obtained. However, from the application perspective, there are still a series of problems. Therefore, coal mine safety risk early warning model and early warning decision support system based on multi-source information are designed. Its potential economic and social benefits are analyzed to provide services for coal mine safety production. This is still an urgent problem that needs to be solved. Based on this, it is of great significance to build the early warning model of gas safety management.

3. Coal and gas outburst stick-slip mechanism and catastrophe theory

3.1 Coal and gas outburst stick-slip mechanism

The friction sliding simulation experiment during coal and gas outburst proved the stick-slip instability in the process of coal and gas outburst. The study on the deformation of the coal rock mass with gas and the stress change of the slip surface showed that the occurrence of coal and gas outburst features the catastrophic change that is rooted in and embodies the stick-slip instability. The stick-slip instability is a very unstable dynamic process. Because of the complexity and variety of stress fields and external forces, the slip surface stress is discontinuous. And when the stress difference reaches a certain value, it will suddenly unload and produce the fluctuation process, making the outburst show the catastrophic change.

3.2 Catastrophe theory of coal and gas outburst

Catastrophe theory is a mathematical method to describe a series of continuous quantitative changes, whose main object is the potential function characterizing the catastrophe system. The catastrophe system is a balance surface composed of the critical points of the potential function, which is to study the discontinuous feature near the critical points to get the bifurcation point set equation. When the control variable satisfies the difference point set equation, the system will suffer catastrophic change.
The catastrophe of coal and gas is a complex catastrophe system, with the concrete equation expression form shown in Table 1. Geology and gas are the control variables of the potential function, and the system is a balance surface composed of the critical points of the potential function. The points of the vertical tangent on the surface consist of the singular point set S of the system, and the projection B of S on the control variable plane is the set of the system's catastrophe, namely the critical point of the coal and gas outburst. The outburst is the transition process of the variables from the lower stable zone to the upper stable zone. When the geology and gas variables are moving along different trajectories in the stable zone, the gas-bearing coal-rock body is in a steady-sliding state. When the variable moves to the edge of the fold in the stable zone, the gas-bearing coal-rock body sees stick-slip friction, leading to the outburst of the system.

Table 1: Expression form of catastrophic system equation

Catastrophe type	Functional formula	Bifurcation equation	Index
Folding catastrophe	F(x)= $\frac{1}{3}x^{2}+ax$	a=0	a
Cusp catastrophe	F(x)= $\frac{1}{4}x^{4}+\frac{1}{2}ax^{2}+bx$	$a=-6x^{2}$	a。b
swallowtail	F(x)= $\frac{1}{5}x^{5}+b\frac{1}{3}x^{3}+c\frac{1}{2}x^{2}$	b= $-3x^{2}$	a。b。c

4. Establishment and solution of the model

4.1 Model I: judge gas content of coal mines

Six monitoring points were set: Mining Surface I, Mining Surface II, Heading Face, Return Air Lane I, Return Air Lane II, General Return Air Lane K (k= 1, 2, ..., 6). The morning, noon, and evening shifts were numbered as j= 1,2,3.

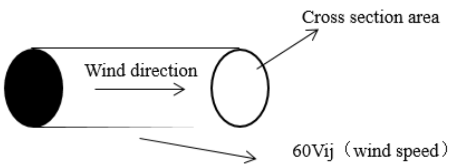

Figure 1: Sketch map of coal mine ventilation

(1) Calculation of Absolute Gas Emission Amount
The absolute gas emission amount of the k monitoring point in j shift on i day can be calculated as follows. First, calculate the volume of the gas passing through the cross-section, and then multiply the gas volume by the concentration proportion of the gas, namely c%, leading to the volume of gas produced per unit time, expressed in various quantities and calculated by the following formula: Qijk= 60VijkSkCijk%60Vijk. With the distance the wind blows per minute (m) and the Qijk above, the average absolute gas emission amount of the K monitoring point can be calculated with the following formula:

$$Q = \frac{1}{90}\sum_{i=1}^{30}\sum_{j=1}^{3} Qijk$$

(2) Calculation of Relative Gas Emission Amount
According to the definition of relative gas emission, the relative gas emission amount of the i day can be expressed in the following expression:

$$Wijk = \frac{24 * 60Qijk}{Ai}(i = 1,2,3...,30)$$

The absolute gas emission from each shift of each monitoring point can be calculated by the above model. The Coal Mine Safety Production Rules will help to judge the coal mine as high-gas-content or low-gas-content mine. (Qijk: the absolute gas emission amount (m3/min) of the K monitoring point for the i day of j shift)

4.2 Model II: Judge the Insecurity in Coal Mines

There are two possible causes of explosions in coal mines: coal dust explosions and gas explosions. Here is the explosion possibility of both. As for the possibility of coal dust explosion, this paper, based on the data of annexed, carried out a fitting to get the function relation of the gas concentration Cijk and the lower bound of the coal dust explosion Y as follows in Figure 2.

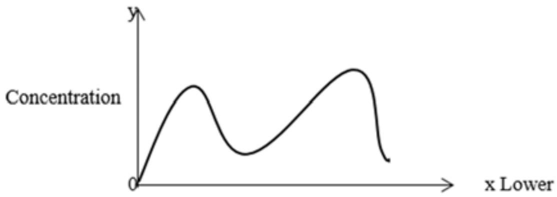

Figure 2: Function diagram

4.3 Early warning guidelines

The following guidelines should be followed for the impact of early warning indicators on coal and gas outburst:
(1) Non-complementary Principle. If the effect of each early warning index on coal and gas outburst is different and cannot be substituted for each other, the minimum value of xa, xb, xc, and xd should be taken as the system catastrophe level according to the minimax principle.
(2) Complementarity Principle. If the role of early warning indices can be substituted or make up for each other, the average value of xa, xb, xc, and xd is taken as the system catastrophe level.

5. Application of coal and gas outburst early warning catastrophe model

5.1 Research on factors affecting gas outburst

(1) Geological Structure. 8 out of the 18 gas dynamic activities are related to faults at Yuwu Coal. The statistical analysis of the above-standard situation of the drill cuttings gas desorption index shows that the number of above-standard cases in the structural belt is about 75% of the total above-standard cases, and most of them are accompanied by soft stratification and coal thickness changes, so the geological structure is the main contributor to the coal and gas outburst of Yuwu Coal.
(2) Gas Occurrence Characteristics in the Coal Seam. The gas occurrence in the coal seam of Yuwu Coal is largely affected by the geological structure, and increases with the increase in the thickness of coal seam, overburden bedrock and the top and bottom trays of the surrounding rock, and buried depth.
(3) Features of Deformed Coal. Under the influence of the slip-sheet structure, the deformed coal in local area of the well field is highly developed, while the deformed coals at the bottom of coal seam and fault zone are often developed into granulated coal and mylonitized coal with the outburst potential. The statistic of the gas desorption index of drill cuttings shows that the above-standard cases for deformed coal is 48%.

5.2 Selection of early warning index

The coal and gas outburst of Yuwu Coal is mainly caused by gas geologic anomaly. Gas dynamic phenomenon of the coal mine always occurs in geological anomaly zone, and the gas volume fluctuates before the dynamic phenomenon occurs. Therefore, the outburst early warning index must be sensitive to the abnormal condition of gas geology. On the basis of mine gas geology research, combined with daily management experience of outburst prevention, the paper selected the early warning index of coal and gas outburst for Yuwu Coal, and decomposed the coal and gas outburst system into a layered system composed of early warning index according to the primary and secondary relationship of the standard layer of the early warning index system (Figure 3).

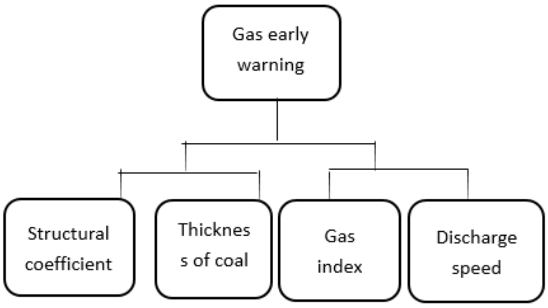

Figure 3: Stratified system

5.3 Early warning grading and model application

Combined with the site situation and the simplicity of early warning, this paper divided the Yuwu Coal early warning levels into Level I (no risks), Level II (outburst threat), and Level III (outburst danger). According to the Regulation on the Coal and Gas Outburst Prevention and Handling and Yuwu Coal's previous experience, the alarm interval of each warning index was determined, and the early warning indexes were regulated to convert to the initial membership degree between 0~1.

In the specified early warning period, the coal and gas outburst early warning index of Yuwu Coal was valued to get the discrete quantity value, in which the qualitative index, such as the coefficient of structural complexity and the variation of coal thickness, was determined by Yuwu Coal's experience of mine outburst prevention (Table 2).

Because of the different dimensions of early warning indicators, the catastrophe fuzzy membership function could not be applied into the calculation of the catastrophe level. Thus, it was necessary to rule the original data, and then apply the catastrophe fuzzy function method to synthesize from the lower index upward by layer, leading to the catastrophe level according to the fuzzy membership function of the swallowtail catastrophe and the principle of index complementary. Compare the catastrophe level and warning boundary (The boundary between Level □ and Level □ was 0.848, and that between Level II and III was 0.928) to get the warning degree at different early warning periods. For example, in the early warning time period on September 19th, 2011, C1, C2 and C3 constituted the swallowtail catastrophe to bring the geologic index B1 of the composition criterion Layer B1, and then B1 and B2 constituted the cusp catastrophe.

$$B_1 = \frac{1}{3}(\sqrt{C_1} + \sqrt[3]{C_2}) \qquad B_2 = \frac{1}{3}(\sqrt{C_4} + \sqrt[3]{C_2} + \sqrt[4]{C_2})$$

According to the cusp catastrophe model, the catastrophe level A was calculated. During this early warning period, the level was less than 0.848, and S2206 tape heading working face was in the safe state without outburst danger. By the same token, we can get the warning degree at different warning periods and realize early warning.

Table 2: Warning indicator table

Qualitative index	Grade I	II	III
Thickness of coal seam	Shallow thickness	Thicker	Depth of thickness
Quantized value of index	0-1	1-2	*2-3*

6. Analysis of early warning results

Through the excavation engineering practice, the value of drill cuttings gas desorption index continuously exceeded the standard, indicating that the early warning results and the actual conditions match, with the degree of conformity as shown in Figure 4. In other early warning periods, the catastrophe levels were all less than 0.848, with the working face in the safe state and the gas volume changing between 0~0.2% in the early warning periods, a low fluctuation within the standard. Also, the value of the drill cuttings gas desorption index did not exceed the limit, and the excavation process did not see gas dynamics phenomenon, showing the conformity of the warning results and the actual conditions. It can be seen that the application of stick-slip instability and catastrophe theory to coal and gas outburst warning is feasible and has practical value.

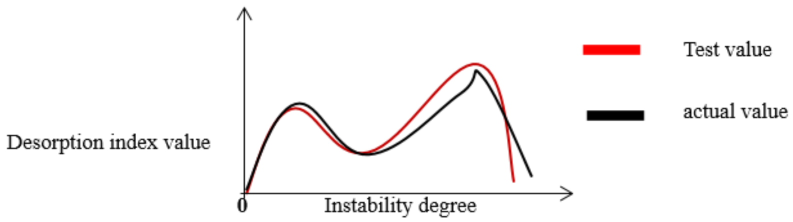

Figure 4: the early warning results and the actual conditions match, with the degree of conformity

7. Conclusion

(1) In the coal and gas outburst stick-slip instability– catastrophe early warning model, the inherent mechanism of the catastrophe fuzzy membership function to quantify the importance of the early warning index overcomes the disadvantage that the general model needs the specific calculation of index weights that may be influenced by subjective factors.
(2) The fuzzy model can better deal with the multi-attribute decision problem of the outburst complex system, and the stick-slip instability– catastrophe warning model is reliable in handling the index complementary and non-complementarity, providing a new solution to the index complementary and non-complementarity problem in the coal and gas outburst early warning.
(3) The application into the early warning for S2206 belt driving face of Lu'an Huan Energy Co., Ltd. Yuwu Coal indicated that early warning result of the model is consistent with the actual conditions and can technically support the coal and gas outburst early warning.

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