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Situation Assessment Model of Rock Burst Based on the Multi-source Information Fusion

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Abstract: Rock burst is one of the main coal mining hazards in China. In recent years, digital reconstruction has been applied to detecting system and valuable data have been obtained in some large coal mine. However, how to find out origin and mechanism of the rock burst and how to improve the overall prediction and prevention is still the urgent subject of the research. This study describes how to build the indicator system of rock burst with the theory of situation assessment and furthermore presents the quantitative evaluation method of its assessment based on multi-source information fusion. Through this method, rock burst situation value samples are calculated from data got from the monitoring system. Then the reliability of the rock burst warning can be calculated by time series analysis. Simulation examples verify its high precision in the quantitative evaluation method and intuitionally reflect the tendency to occur the rock burst.

Key words: Rock burst, situation assessment, information fusion, prediction and warning

INTRODUCTION

Situation assessment study on rock burst is a hot issue in the field of mine safety. As the mining depth increases and geological conditions deteriorate, the rock burst hazard becomes one of the typical dynamic hazards in coal mining which poses a serious threat to the miners' safety and affects social stability and damage the coordinating development of the ecological environment and economy. The causes of accidents are varied, such as mining activities, geographical condition, inadequate understanding of rock burst mechanism, lack of funds, outdated technology and so on (Qi and Dou, 2006; Minggao *et al*., 2010; Dou and He, 2001).

For the past few years, monitoring systems (i.e., micro-seismic monitoring system, rock pressure monitoring system, acoustic emission monitoring system and the roof separation monitoring system) have been put into use and valuable data have been got in many coal mine (Pan *et al*., 2011; Xia *et al*., 2010; Wang *et al*., 2007; Dou *et al*., 2007). However, how to develop a comprehensive system of evaluation and control of this hazard is still the urgent subject of the research.

In the study, the situation assessment model has been employed in rock burst detection. Based on microseism monitoring system, rock pressure monitoring system, acoustic emission monitoring system, electromagnetic radiation monitoring system and the roof separation monitoring system, a multi-source identification of premonitory technology was formed. Thus its dynamic tendency can be appropriately reflected by time series analysis methods. The results show the method can get more accurate results and better real-time characteristic. As an important technology in the coal mine production safety, rock burst situation assessment is an application of great significance.

DEFINITION AND FORMAL REPRESENTATION OF THE CORE ELEMENTS

The study attempts a definition of the core elements of the situation assessment model of rock burst including: Rock-burst Tendency, Rock-burst Expectant, Happened Probability and Rock-burst Situation.

Definition 1

Rock-burst tendency: Rock-burst tendency reflects the inherent properties of coal and rock materials to induce a rock burst and its formalization written as $S_{rbt} = \{S_0, S_1, S_2, S_3, S_4, S_5\}$ S_0-very weak rock-burst tendency, S_1-weak rock-burst tendency, S_2-medium rock-burst tendency, S_3-weak strong rock-burst tendency, S_4-strong rock-burst tendency, S_5-very strong rock-burst tendency.

Definition 2

Rock-burst expectant: Rock-burst expectant refers to the its occurrence probability based on the real time and historic data obtained by on-line monitoring system. Formal representation definition is $P_{id}(\bar{A}) = 1\text{-}P_{id}(A)$, $P_{id}(A)\in[0, 1]$, where, id is the unique identifier of the monitoring system, A represents a rock burst occurred and $\bar{A}$ a rock burst does not occur.

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Definition 3

Happened probability: Happened probability refers to the probability of occurrence of the rock burst. Formal representation definition is $\delta_{hp} \in [0, 1]$. Happened probability is calculated by the improved algorithm of D-S evidence theory method based on a number of the $P_{id}(h)$.

Definition 4

Rock-burst situations: Rock-burst situation reflects the actual quantization values of rock burst situation. Formal representation definition is $\delta_{rs} \in [0, 1]$. According to actual monitoring parameters to correct the Happened Probability; the results accurately reflect the tendency to occur a rock burst.

SITUATION ASSESSMENT MODEL OF ROCK BURST

The rock burst situation assessment model framework (Fig. 1) is divided into two parts: Rock burst situation assessment and prediction.

The quantitative assessment of rock burst situation is obtained by reading the system log information and real-time monitoring data from detecting system including micro-seismic monitoring system, mine pressure monitoring system, acoustic emission monitoring system and the roof separation monitoring system. Log auditing has been introduced to get Rock Burst Expectant and D-S evidence theory is used to get its Happened Probability. At the same time, use actual monitoring parameters to modify the Happened Probability. Then quantitative values which accurately reflect the rock burst situation can be got.

Time series analysis algorithm which is based on the quantitative assessment of rock burst situation is used to predict the tendency to occur the rock burst. This study describes how to use GM (1, 1) to predict the rock-burst tendency.

QUANTITATIVE ASSESSMENT ALGORITHM OF ROCK BURST SITUATION

Assume that the early alarm log collection is called LS_p and the actual data from the monitoring system Log collection is set in LS_d, then calculate of the probability of each monitoring system for and against of occurring the rock burst. Using the improved D-S evidence theory, comprehensive support probability of occurring the rock burst that is based on each monitor system can be obtained. The algorithm process is designed as follows:

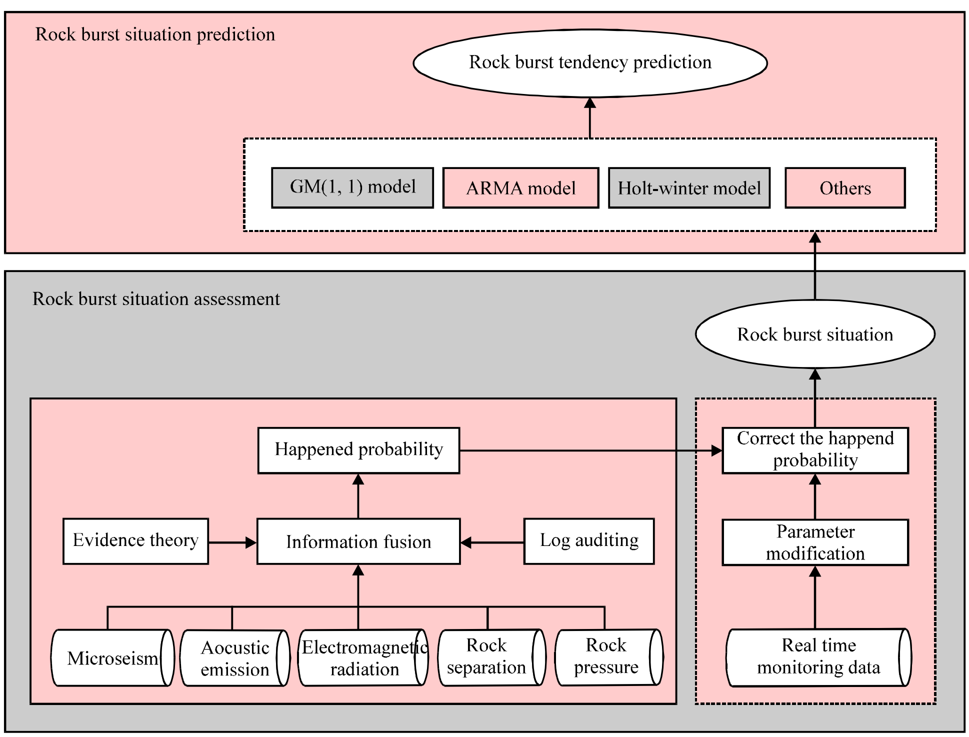

Fig. 1: Situation assessment model of rock burst

- **Calculation of the probability of each monitoring system supporting for occurring the rock burst:** Assume that the alarm log collection is called LS_p and the actual data Log collection from the monitoring system is set in LS_d. LS_p contains the rock burst warning information from monitoring system which is composed of a number of logging and warning weight value, application triples expressed as: LS_p (id, α, w), where id represents the unique identifier of the monitoring system, α represents the system warning category coding and w represents warning weight values. Similarly, the multiple logging and warning weight values compose of LS_d (id, α, w). Use LS_d and LS_p to carry out matching analysis so as to get the successfully matched log collection LS_s (id, α, w) that w represents the weight value for each record. Now assume that $P_{id}(A)$ represents Happened Probability of the rock burst got from monitoring system. The rule is:

$$P_{id}(A) = \sum_{i=1}^{r} w_i \quad (1)$$

where, r stands for the number of the successfully matched log records, $P_{id}(\bar{A}) = 1\text{-}P_{id}(A)$ and $P_{id}(A) \in [0, 1]$

- **The fusion of happened probability of each monitoring system based on improved D-S evidence theory:** The theory of evidence proposed by Glenn Shafer is an extension of the idea developed by Dempster (1967) for use with Bayesian probabilities during the 1960's to subjective evidence. This study is commonly referred to as Dempster-Shafer Theory (Shafer, 1976). It provides a combined evidence method based on the multi-source information. D-S theory represents the relevant characteristics of the world as a finite set of mutually exclusive propositions and assumptions called the frame of discernment. Traditionally, the notation of a capital Greek letter (e.g., Θ) is used for both the frame of discernment and the set of propositions within any frame of discernment. The 2^{Θ} subset of the frame of discernment form a collection of propositions. For any proposition A in the problem domain, there are $A \in 2^{\Theta}$. If the mass function m: $2^{\Theta} \rightarrow [0, 1]$ satisfies:

$$\begin{cases} m(\Phi) = 0 \\ \sum_{A \subset \Theta} m(A) = 1 \end{cases} \quad (2)$$

where, Φ represents empty set and m is the basic belief of number of the frame of discernment and m(A) is called A's basic belief number or the mass of A

The integrated Happened Probability of the occurring the rock burst will be obtained by fusing data from monitoring systems. So the frame of discernment written as Θ = {A, A} and the power set is 2^{Θ} = {Φ, {A}, {A}, H}, where, Φ represents the unlikely event that the rock burst both occur and without the occurrence, H represents the rock burst both may occur, or may not happen. So, the mass function of monitoring system can be expressed as:

$$m_{id}(\Phi) = 0;\ m_{id}(A) = P_{id}(A);\ m_{id}(\bar{A}) = P_{id}(\bar{A});\ m_{id}(H) = 0 \quad (3)$$

The conditioning rule which governs the normalization of the combined evidence, may leads to counterintuitive averaging of conflicting evidence (Yager, 1987; Lefevre *et al*., 2002; Yamada, 2008; Jousselme *et al*., 2001; Hu *et al*., 2009; Jia *et al*., 2010). So, the improved D-S evidence theory is applied to mass function value of the monitoring system. According to the relative weighting of the evidence of fusion algorithm presented by Li *et al*. (2002), Derivate of the happened probability of synthesis formula for n-set monitoring system.

$$\begin{cases} m(\Phi) = 0 \\ m(A) = \prod_{id=1}^{n} m_{id}(A) + \lambda \times f(A) \\ m(\bar{A}) = 1 - m(A) \\ m(H) = 0 \end{cases} \quad (4)$$

Where:

$$\lambda = 1 - \prod_{id=1}^{n} m_{id}(A) - \prod_{id=1}^{n} m_{id}(\bar{A}),\ f(A) = \frac{1}{n}\sum_{id=1}^{n} m_{id}(A)$$

Based on the information fusion of multiple data sources through the introduction of the improved D-S evidence theory, the probability of occurrence of the rock burst δ_{hp} = m(A) will be obtained which reflects the integrated results of the monitoring systems.

REAL-TIME CORRECTION ALGORITHM OF ROCK BURST SITUATION

If only depend on multi-source information fusion with data from the system log, the happened probability of rock burst is still not accurately reflect the security situation in the rock burst and therefore the real-time correction algorithm of rock burst situation is proposed to use the real-time monitoring system data on the rock burst situation to amend.

The monitoring feature set in the assessment model of rock burst situation is defined as the five-tuple:

$$D = \{\omega, \gamma, \mu, \rho, \sigma\}$$

where ω, γ, μ, ρ, σ represent the data from the monitoring system of rock pressure, microseismic, electromagnetic radiation, acoustic emission, roof separation, respectively. In view of the different technical principles of the each monitoring system, the feature vector can be a separate indicator data can also be a multiple indicator data. Let {ω, γ, μ, ρ, σ} the minimum values be 0, the definition of the monitoring system for early warning value is $\{\omega_0, \gamma_0, \mu_0, \rho_0, \sigma_0\}$. using the following formula to calculate the current happened probability of occurrence of a rock burst:

$$P_D = 1-\frac{1}{5}\left(\frac{\omega}{\omega_0}+\frac{\gamma}{\gamma_0}+\frac{\mu}{\mu_0}+\frac{\rho}{\rho_0}+\frac{\sigma}{\sigma_0}\right) \quad (5)$$

If ω≥ω, then $\omega/\omega_0 = 1$, similarly, γ≥γ, $\gamma/\gamma_0 = 1$ and so on. Easy to know that $P_D \in [0, 1]$.

At the beginning of a period, the monitoring feature set is $\{\omega_1, \gamma_1, \mu_1, \rho_1, \sigma_1\}$ and at the end of that period, monitoring feature set is $\{\omega_2, \gamma_2, \mu_2, \rho_2, \sigma_2\}$, by the formula 5 the following value can be calculated:

$$P_{D1} = 1-\frac{1}{5}\left(\frac{\omega_1}{\omega_0}+\frac{\gamma_1}{\gamma_0}+\frac{\mu_1}{\mu_0}+\frac{\rho_1}{\rho_0}+\frac{\sigma_1}{\sigma_0}\right)$$

$$P_{D2} = 1-\frac{1}{5}\left(\frac{\omega_2}{\omega_0}+\frac{\gamma_2}{\gamma_0}+\frac{\mu_2}{\mu_0}+\frac{\rho_2}{\rho_0}+\frac{\sigma_2}{\sigma_0}\right)$$

$$\Delta P_D = \frac{1}{5}\left(\frac{\omega_2-\omega_1}{\omega_0}+\frac{\gamma_2-\gamma_1}{\gamma_0}+\frac{\mu_2-\mu_1}{\mu_0}+\frac{\rho_2-\rho_1}{\rho_0}+\frac{\sigma_2-\sigma_1}{\sigma_0}\right)$$

Then use ΔP_D to amend the happened probability written as δ_{rs} and the probability of occurring a rock burst written as δ_{rs} is calculated as follows:

$$\delta_{rs} = (1-\xi)\times\delta_{hp}+\xi+\Delta P_D \quad (6)$$

where, $\xi \in [0, 1]$ is the correction parameters which represents the proportion of the measured values in the calculation of the occurring a rock burst.

PREDICTION ALGORITHM OF THE ROCK BURST SITUATION BASED ON GM (1, 1)

The gray system theory (Deng, 1986) has been widely used. It can find out the law of the data from the chaotic, finite, discrete data and then create the corresponding gray model. The following gives the prediction algorithm of the rock burst situation based on an order gray model GM (1, 1).

Step 1: Testing and processing the data of rock burst situation

Set $x^{(0)} = (x^{(0)}(1), x^{(0)}(2),\ldots, x^{(0)}(n))$, the ratio of series can be calculated by the formula 7:

$$\lambda(k) = \frac{x^{(0)}(k-1)}{x^{(0)}(k)}, k = 2,3,\ldots,n \quad (7)$$

If λ_k falls within the coverage of $(e^{-\frac{2}{n+1}}, e^{\frac{2}{n+2}})$, then the sequence $x^{(0)}$ can be used for GM (1, 1) model, otherwise need to transform it fall into coverage. Take appropriate constant c for the translation transformation:

$$y^{(0)} = x^{(0)}(k)+c, k = 1, 2,\cdots, n$$

And so that, the ratio of the two in $y^{(0)} = (y^{(0)}(1), y^{(0)}(2),\ldots, y^{(0)}(n))$ satisfies:

$$\lambda_y(k) = \frac{y^{(0)}(k-1)}{y^{(0)}(k)} \hat{I}(e^{-\frac{2}{n+1}}, e^{\frac{2}{n+2}}), k = 2,3,\ldots,n$$

Step 2: The establishment of GM (1, 1) model.

Do a accumulated generating Operation in Series $x^{(0)} = (x^{(0)}(1), x^{(0)}(2),\ldots, x^{(0)}(n))$

$$x^{(1)} = (x^{(1)}(1), x^{(1)}(x)+x^{(0)}(2),\cdots, x^{(1)}(n-1)+x^{(0)}(n))$$

Where:

$$x^{(k)} = \sum_{i=1}^{k} x^{(0)}(i), k=1,2,\ldots,n$$

And average series can be got:

$$z^{(1)}(k) = 0.5x^{(1)}(k)+0.5x^{(1)}(k-1), k = 2, 3,\cdots,n$$

Then $z^{(1)} = (z^{(1)}(2), z^{(1)}(3),\ldots, z^{(1)}(n))$. So, the establishment of gray differential equation as follows:

$$x^{(0)}(k)+az^{(1)}(k) = b, k = 2, 3,\cdots,n$$

The corresponding differential equation is:

$$\frac{dx^{(1)}}{dt} + ax^{(1)}(t) = b \quad (8)$$

The above equation a, b represent for unknown parameters of the model and are recorded as:

$$u = (a,b)^T, Y = (x^{(0)}(2), x^{(0)}(3),\ldots, x^{(0)}(n))^T, B = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ M & M \\ -z^{(1)}(n) & 1 \end{bmatrix} \quad (9)$$

Table 1: Value of rock burst situation and its tendency

Value of rock burst situation	Tendency of rock burst
$0.0\leq\delta_{rs}<0.1$	S_0
$0.1\leq\delta_{rs}<0.2$	S_1
$0.2\leq\delta_{rs}<0.4$	S_2
$0.4\leq\delta_{rs}<0.6$	S_3
$0.6\leq\delta_{rs}<0.8$	S_4
$0.8\leq\delta_{rs}=1.0$	S_5

Then use least squares method to solve Eq. 8 can get:

$$x^{(1)}(k+1)=(x^{(0)}(1)-\frac{b}{a}e^{-ak}+\frac{b}{a}),\ k=1,2,...,n-1$$

Later establishing GM (1, 1) model, the predictive value will be obtained:

$$\hat{x}^{(1)}(k+1)=(x^{(0)}(1)-\frac{b}{a}e^{-ak}+\frac{b}{a}),\ k=1,2,...,n-1 \quad (10)$$

Where:

$$\hat{x}^{(0)}(k+1)=\hat{x}^{(1)}(k+1)-\hat{x}^{(1)}(k),\ k=1,2,...,n-1$$

Step 3: Testing predict values

- Residual testing. Residual written as $\varepsilon(k)$ can be calculated by the formula 11:

$$\varepsilon(k)=\frac{x^{(0)}(k)-\hat{x}^{(0)}(k)}{x^{(0)}(k)},\ k=1,2,...,n \quad (11)$$

- Deviation testing. The deviation written as $\rho(k)$ can be obtained by the formula 12:

$$\rho(k)=1-\left(\frac{1-0.5a}{1+0.5a}\right)\lambda(k) \quad (12)$$

If $\varepsilon(k)$, $\rho(k)$ are less than 0.2, the results can reach the general requirements, less than 0.1 meet the higher requirements.

Step 4: Predicting the rock burst situation

Calculating the value of rock burst situation in the different periods and drawing the curve in chronological order. The value of the rock burst situation and its tendency is shown in Table 1.

SIMULATION ANALYSIS

Example 1: Select the log collection of a coal mine which record data from monitoring system of microseismic, rock pressure, electromagnetic radiation, acoustic emission and roof separation during Apr. 2011 to Jul. 2011. Define the early alarm log collection written as LS_p which consists of a number of logging and warning weight value pre-defined by expert. Use the early alarm log collection written as LS_p to match monitoring log collection LS_d and in accordance with the formula 1 the support probability of occurring a rock burst for each monitoring system is calculated. By the formula 4 use D-S evidence fusion to fuse the support probability of occurring a rock burst for each monitoring system. Then get the quantitative value of the rock burst (where $\xi = 0.5$) by the formula 6 which amend the happened probability of the rock burst. The calculation results are shown in Table 2. Each time period in the table is for 10 days.

Table 2: Results of rock burst situation calculated by multi-source information fusion model (Date from Apr. 2011 to Jul. 2011)

Time scale	δ_{rs}	Time scale	δ_{rs}
1	0.05	7	0.23
2	0.07	8	0.30
3	0.06	9	0.29
4	0.08	10	0.32
5	0.10	11	0.45
6	0.15	12	0.59

The predicted values of the rock burst situation can be got based on first-order gray prediction model GM (1, 1). The comparison results of actual values and predicted values are shown in Fig. 2a.

The curve demonstrates that it can intuitively reflect the tendency to occur the rock burst situation and actual values show a good agreement with those calculated by the GM(1, 1). This is also consistent with the actual situation.

Example 2: Continue to select monitoring log collection of the same coal mine during Aug. 2011 to Nov. 2011. Because the tendency to occur rock burst on the pre-face is increasingly clear, The measures of water injection and drilling relief measures are taken to optimize the exploitation of design, so the tendency to occur the rock burst is downward. The probability of tendency to occur the rock burst is given in Table 3. Each time period is still 10 days. The trendy of the rock burst situation can be simulated by the Matlab programming based on the data from Table 3, the comparison results of actual and predicted value is shown in Fig. 2b.

Table 3: Results of rock burst situation calculated by multi-source information fusion model (Date from Aug. 2011 to Nov. 2011)

Time scale	δ_{rs}	Time scale	δ_{rs}
1	0.53	7	0.22
2	0.52	8	0.19
3	0.38	9	0.12
4	0.32	10	0.11
5	0.29	11	0.08
6	0.30	12	0.07

The analysis showed that the more accurate data can be obtained to reflect the trendy of rock burst situation. The study is based on D-S evidence fusion assessment

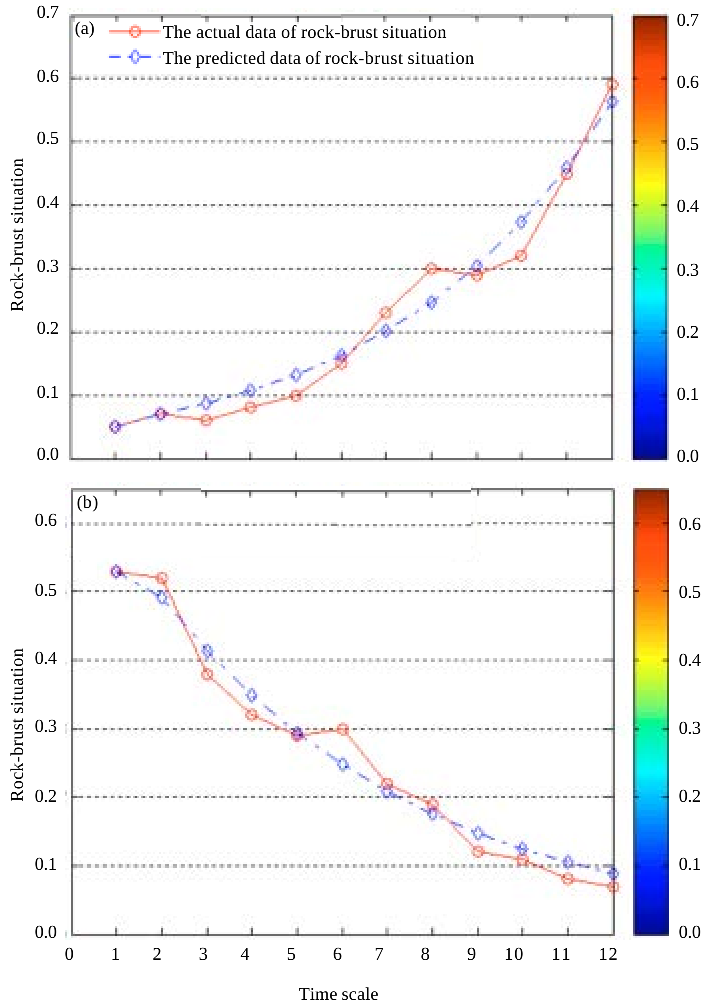

Fig. 2(a-b): Comparison between actual and predicted result of rock burst situation, (a) The actual result based on Table 2 and predicted result calculated with GM(1, 1) model (Date from Apr. 2011 to Jul. 2011) and (b) The actual result based on Table 3 and predicted result calculated by GM(1, 1) model (Date from Aug. 2011 to Nov. 2011)

model and log audit law which combine the log analysis results and actual monitoring data effectively. So, it can reflect the trendy of the rock burst more accurately than traditional methods.

CONCLUSION

- This study conduct the research on monitoring parameters related to the security situation assessment of the rock burst. Taking into account the situation assessment of the rock burst, a more comprehensive monitoring of indicator parameters have been formalized which represent the support probability of occurring a rock burst for each monitoring system. Based on those indicator parameters, the overall dynamic trendy of the rock burst situation can be obtained by combining monitoring system log mining and real-time correction algorithm
- The quantitative assessment algorithm which can get the reference values to quantify the trendy of the current rock burst situation is proposed. Then use the GM(1, 1) forecasting model to predict the security of rock burst situation based on time series and map out the results of the assessment and prediction value in the figure. By the method of visual expression, it can help engineers and technicians understand the current rock burst tendencies

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