

Sensitivity study and application of prediction indicators for coal and gas outburst risk in Yuxi coal mining faces

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Abstract: To reasonably determine the sensitive indicators for predicting coal and gas outburst hazards in mining faces, this study employs mathematical modeling to process measured drill cuttings gas desorption data through dimensionless and standardized treatment, calculating their sensitivity functions and identifying their sensitivity. The results indicate that among the three indicators used for outburst prediction, the drill cuttings gas desorption index K_1 is more sensitive than the drill cuttings gas desorption index Δh_2 and the drill cuttings volume S . Thus, K_1 can serve as the sensitive indicator for predicting coal and gas outburst hazards in this mining face. When the K_1 value exceeds the internal control threshold of $0.4 \text{ mL}/(\text{g} \cdot \text{min}^{1/2})$, abnormal phenomena such as borehole spraying, bit jamming, abnormal gas emission from drill holes, or coal burst sounds may occur during drilling, and the more significant the K_1 value, the more pronounced the dynamic effects. Comparative analysis of field test data shows that the mathematical model's analysis results are largely consistent with actual observations, ultimately confirming the drill cuttings gas desorption sensitive indicator for the test area. Through practical application of the sensitive indicator for coal and gas outburst hazard prediction in the 1306 mining face of a certain mine, favorable outcomes were achieved.

Keywords: Sensitive indicators; Coal and gas outburst; Mathematical analysis; Dimensionless

1 Introduction

Coal and gas outburst is the result of the combined effects of geostress, gas pressure, the weight of coal and rock masses, and their inherent physical properties, constituting an abnormal gas dynamic phenomenon [1-3]. Numerous outburst prediction indicators are employed globally in coal mines involving outburst prevention measures. Typically, coal samples are extracted from coal seams, and the released gas is measured using instruments to assess the outburst risk. Alternatively, coal samples are sieved into fragments of varying particle sizes, and the weight of the coal fragments is measured—greater weight correlates with higher outburst risk. Multiple factors influence the outburst risk, including coal hardness, geological structure, moisture content, and coal pore structure [4-5].

Agrawal Harshit [6] established a probabilistic risk assessment framework for complex engineering phenomena such as heterogeneous coal seam rockburst and gas outburst, and analyzed the probability of coal and gas outburst and safe mining conditions occurring. Yang Li [7] proposed a deep coal and gas outburst hazard prediction method based on kernel principle component analysis and an improved extreme learning machine algorithm to address the problems of low accuracy and efficiency in predicting coal and gas outbursts in deep mines. In order to achieve dynamic, continuous, and real-time prediction of coal and gas outburst hazards in blasting excavation working faces, Qiu Liming [8] proposed a outburst hazard prediction method based on the characteristics of gas outburst after blasting. Tao Hu [9] studied the characteristics of outburst parameters and gas desorption laws under different moisture contents, and obtained the influence of moisture content on outburst prediction parameters. Lingran Ren [10] established a new prominent hazard index based on the characteristic that temperature changes occur before the decrease of acoustic emission signals.

In engineering practice, the indicators for predicting and judging the risk of coal and gas outburst mainly include: drilling cuttings gas desorption indicators K_1 and Δh_2 , initial gas emission velocity index q , drilling cuttings quantity

DOI: 10.67762/jye9xt79

Submission date: June 9, 2026

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index S, R index method, etc., and combined with the acoustic omen and silent omen at the construction site to make a comprehensive judgment. The commonly used prediction indicators indirectly and partially reflect the three prominent prediction elements of geostress, gas pressure, and the physical properties of coal itself. However, for different mines or even different areas of coal seams in the same mine, the dominant factors of outburst may vary, which requires sensitivity testing of the selected prediction indicators [11]. There is a certain correlation among the pore structure, strength and initial gas desorption capacity of coal, which can be used for outburst risk identification [12]. Reference [13] investigated the critical values of sensitive indicators for coal-gas outburst prediction in deep complex coal seams, and provided corresponding methods and application cases. Reference [14] carried out experimental research on the sensitivity of outburst risk prediction indicators for primary and tectonic composite coal seams.

2 Background of Experimental Engineering

The Yuxi coal mining area of a certain coal mine is 26.147km², and the approved mining capacity of the 3 # coal seam is 2.4Mt/a. The geological reserves are $2.16 \times 108t$, and the recoverable reserves are $1.42 \times 108t$. The mine is currently mining the +320 level 3 # coal seam, with an average thickness of 5.85m and an average dip angle of 6°. It is divided into four mining areas: mining area one, mining area two, mining area three, and mining area four. Mining area one is located in the south of the mine field, mining area two is located in the middle of the mine field, mining area three is located in the northeast of the mine field, and mining area four is located in the southeast of the mine field. The first mining area of the mine has completed the backfilling of the 1301 and 1302 north working faces. There is currently one backfilling face (1303 mining face), one dismantling face (1304 dismantling face), one backup face (1305 backup face), and two coal roadway excavation faces (1302 south belt trench excavation face and 1306 return air trench excavation face) underground. The direct roof of the coal seam is composed of sandy mudstone with an average thickness of 5.3 meters, while the main roof is composed of fine-grained sandstone with an average thickness of 5.5 meters. The bottom rock layer consists of black mudstone with an average thickness of 0.7 meters and K7 sandstone with an average thickness of 3.35 meters.

The gas content in the No. 3 coal seam of the first mining area of the coal mine is 15.43-18.68m³/t, and the original gas pressure is 1.65MPa, which poses a risk of coal and gas outburst. Due to geological tectonic activity, soft coal with a thickness of 0.1-0.5m is developed approximately 1m below the coal seam roof. Coal seams have low permeability, are not prone to spontaneous combustion, and coal dust is non explosive.

3 Experimental Investigation of Prediction Indicators for Coal and Gas Outburst

At present, the gas desorption index method of drilling cuttings is commonly used in outburst mines to test the risk of coal and gas outbursts. Generally, the gas desorption indicators K₁, Δh_2 , qvalue, drilling cuttings quantity S, R value method or one or two of them are used to predict or test whether there is a risk of coal and gas outburst in coal seams. However, due to differences in burial depth and geological conditions, coal seams in different areas of each mine or even the same field are also affected to some extent by external conditions such as on-site testing conditions, instrument performance, and operator responsibility, as well as human factors, resulting in significant differences in the regularity and sensitivity of various indicators. It is difficult to make correct judgments solely based on experience. When testing in a certain area, theoretically speaking, the size of the predicted indicators does not match the on-site prominent premonition, which requires examining and analyzing the sensitivity of each testing indicator.

The 1306 return airway coal roadway excavation working face was selected as the experimental investigation site for this experiment, and K₁ value, Δh_2 , and S value were used as prediction indicators. The following critical values were used as references for each prediction indicator: K₁=0.5mL/(g·min^{1/2})、 Δh_2 = 200Pa、S=6.0kg/m. When any indicator in the prediction or inspection exceeds the critical value, or when there are obvious signs of coal and gas outburst such as spraying, suction drilling, and top drilling during the construction drilling process, the working face is classified as having coal and gas outburst danger. Otherwise, it is classified as a non outburst danger working face.

3.1 Mathematical modeling of predictive indicators

Due to significant differences in the numerical values and units of the gas desorption indicators K₁ and Δh_2 , as well as the amount of drilling cuttings S, it is necessary to standardize the predicted results of each indicator in order to offset their differences in magnitude and units. Here, the mean operator is used to convert the numerical values of

each indicator as follows.

3.1.1 Non-dimensionalization of prediction indicators

The dimensionless transformation of various indicators with different units is for the convenience of comparative analysis. The dimensionless transformation can be processed using the following formula

$$X_i = \frac{X_i - \bar{X}}{C} \quad (i=1.2.3\dots n) \quad (1)$$

In the formula :

X_i ——raw data ;

$\bar{X}$ ——the average value of the original data ;

C ——Standard deviation of the original data.

$$C = \sqrt{\frac{1}{n} \sum_{i=1}^n (X_i - \bar{X})^2}$$

3.1.2 Standardization of predictive indicators

Dimensionless normalization involves compressing dimensionless data within the interval [0,1]. The following extreme value normalization formula can be used for this purpose:

$$X_i'' = \frac{X_i' - X_{\min}'}{X_{\max}' - X_{\min}'} \quad (i=1.2.3\dots n) \quad (2)$$

Clearly, when $X_i' = X_{\max}'$, $X_i'' = 1$, and when $X_i' = X_{\min}'$, $X_i'' = 0$. This compresses the standardized data within the interval [0,1].

After the aforementioned two steps of transformation, the outburst prediction indicators K_1 , Δh_2 , and S , which carry different units, have all been converted into dimensionless quantities that vary within the interval [0,1].

3.2 Establishment of sensitivity function

3.2.1 Each discrete index and its mathematical expectation

Before examining the critical values of prediction indicators, coal mines generally use the critical values specified in the "Detailed Rules for Preventing and Controlling Coal and Gas Outbursts" (2019) as a basis. Here, let K_{1qw} , Δh_{2qw} , and S_{qw} represent the mathematical expectations corresponding to the discrete variables of each prediction indicator.

From equation (1), we can convert K_1 , Δh_2 , and S into dimensionless quantities, yielding:

$$K_{1i}' = \frac{K_{1i} - \bar{K}_1}{C} \quad (i=1.2.3\dots n) \quad (3)$$

In the formula

K_{1i} ——Raw data of predictive indicator K_1 ;

$\bar{K}_1$ ——The average value of the original data for prediction indicator K_1 ;

C ——Standard deviation of the predictive indicator K_1 .

$$C = \sqrt{\frac{1}{n} \sum_{i=1}^n (K_{1i} - \bar{K}_1)^2}$$

Similarly, we can derive the dimensionless quantities of Δh_2 and S :

$$\Delta h_{2i}' = \frac{\Delta h_{2i} - \bar{\Delta h}_2}{C} \quad (i=1.2.3\dots n) \quad (4)$$

$$S_i' = \frac{S_i - \bar{S}}{C} \quad (i=1.2.3\dots n) \quad (5)$$

Based on formula (2), we can compress K_1 , Δh_2 , and S , which have been converted into dimensionless quantities, within the interval [0,1]. From this, we can deduce that:

$$K_{1i}'' = \frac{K_{1i}' - K_{1\min}'}{K_{1\max}' - K_{1\min}'} \quad (6)$$

$$\Delta h_{2i}'' = \frac{\Delta h_{2i}' - \Delta h_{2\min}'}{\Delta h_{2\max}' - \Delta h_{2\min}'} \quad (7)$$

$$S_i'' = \frac{S_i' - S_{\min}'}{S_{\max}' - S_{\min}'} \quad (8)$$

The values of K_{1qw} , Δh_{2qw} , and S_{qw} after standardization and compression are defined as $E(K_{1qw})$, $E(\Delta h_{2qw})$, and $E(S_{qw})$, respectively, with the following expressions:

$$E(K_{1qw}) = \frac{K_{1qw}' - K_{1\min}'}{K_{1\max}' - K_{1\min}'} \quad (9)$$

$$E(\Delta h_{2qw}) = \frac{\Delta h_{2qw}' - \Delta h_{2\min}'}{\Delta h_{2\max}' - \Delta h_{2\min}'} \quad (10)$$

$$E(S_{qw}) = \frac{S_{qw}' - S_{\min}'}{S_{\max}' - S_{\min}'} \quad (11)$$

3.2.2 Establish the sensitivity function of the predictive indicator

In mathematical statistics, “bias” reflects the degree of deviation of each discrete indicator from its corresponding mathematical expectation. In the analysis of predictive indicator problems, it reflects the degree of dispersion between each predictive indicator and its corresponding mathematical expectation. Since “bias” can be positive or negative, the average of the sum of squares of each indicator’s “bias” can generally reflect the degree of dispersion of that indicator. Defining this descriptive indicator as $D(X)$, we obtain:

$$D(X) = \frac{\sum_{i=1}^n (X_i - E(X))^2}{n} \quad (12)$$

Define the sensitivity function of the indicator as $M(i)$, order $M(i) = \sqrt{D(X)}$. The following relationship holds:

$$M(i) = \sqrt{\frac{\sum_{i=1}^n (X_i - E(X))^2}{n}} \quad (13)$$

From (1) to (13), we can derive the sensitivity functions $M_1(i)$, $M_2(i)$, and $M_3(i)$ of the prediction indicators K_1 , Δh_2 , and S , expressed as follows:

$$M_1(i) = \sqrt{\frac{\sum_{i=1}^n (K_{1i}'' - E(K_{1qw}))^2}{n}} \quad (14)$$

$$M_2(i) = \sqrt{\frac{\sum_{i=1}^n (\Delta h_{2i}'' - E(\Delta h_{2qw}))^2}{n}} \quad (15)$$

$$M_3(i) = \sqrt{\frac{\sum_{i=1}^n (S_i'' - E(S_{qw}))^2}{n}} \quad (16)$$

By using the above formula, it can be calculated that there is a sensitive relationship between the influencing factors and the risk of coal seam and gas outburst. According to the sensitivity function, the larger the correlation value, the closer the relationship between the two quantities. The sensitivity index with the highest correlation value is the required one. Calculate the sizes of $M_1(i)$, $M_2(i)$, and $M_3(i)$ separately. The larger the value, the more sensitive the corresponding indicator is, and vice versa.

4 Application of sensitivity determination of predictive indicators in the field

The 1306 working face is 239m long (net length), with a mining advance length of 2062m. A 120m protective coal pillar is left at the stop mining line and Xiwasi drainage roadway, and the cutting hole is arranged at the protective coal pillar on the west boundary of the mine field. The burial depth of the 3# coal seam at the 1306 return air chute heading face is 533~741m, the average burial depth is 400m. The roadway has a rectangular cross-section with a width

of 5.7m, a height of 4.3m, and a cross-sectional area of 24.51m².

According to the mining design of the 1306 working face and the actual situation on site, the bottom extraction roadway through layer drilling strip extraction and anti outburst measures were implemented for the 1306 return air trench excavation working face before excavation. The 1306 bottom extraction roadway is designed and divided into 10 units, each covering an area of 204m in length. Each area is designed with 34 rows of drilling holes, with 16 drilling holes per row, for a total of 544 drilling holes. The final hole spacing is 6m, and the drilling holes penetrate the coal seam and enter the roof 0.5m. The designed drilling footage for each area is 16626m, and according to the company's requirements, the extraction time is not less than 6 months. The pre excavation area inspection and sampling of the 1306 return air duct excavation working face meet the standards and are qualified. The maximum residual gas content measured by China University of Mining and Technology in the entire strip area covered by the 1306 bottom extraction roadway drilling site of this mine is shown in Table 1.

Table 1 Gas content in the 1306 return air duct strip area

Drilling site	1306 return air duct control Regional scope (m)	Residual gas content Maximum value (m ³ /t)	Inverse residual gas pressure Maximum value (MPa)
1#-5#	0-204	6.05	0.32
6#-10#	205-408	6.86	0.33
11#-15#	409-613	7.76	0.34
16#-20#	614-817	7.81	0.38
21#-25#	818-1021	4.25	0.18
26#-30#	1022-1225	6.58	0.34
31#-35#	1226-1429	7.83	0.41
36#-40#	1430-1633	5.97	0.31
41#-45#	1634-1837	6.32	0.35
46#-51#	1838-2082	7.41	0.40

4.1 Prediction method and anti outburst measures for working face

4.1.1 Prediction method for working face

On site inspection of the 1306 return air duct excavation working face, the measuring instrument used was the YTC-3 gas outburst parameter meter produced by the Chongqing Branch of the China Coal Science Research Institute. When using the gas desorption indicators K₁, Δh₂, and drilling powder amount S to predict the risk of coal and gas outbursts, the following steps should be followed:

Seven inspection boreholes are arranged in front of the working face, located on the upper, middle, lower, and both sides of the working face. The middle borehole is located in the middle of the tunnel section, parallel to the excavation direction, with a depth of 8-10m and a diameter of 42mm. The final points of the inspection boreholes on both sides are located 2-4m outside the contour lines of the tunnel, at an angle of 15 ° to the tunnel. When soft stratification occurs on the working face, the inspection boreholes should be arranged in the soft stratification as much as possible. When the exposed thickness of the coal body in the roadway changes, the drilling layout will be adjusted. When the danger prediction process of coal and gas outburst in the working face is 0.5>K₁ value>0.4, Δh₂>180, S value>5Kg, or when the coal body is broken, two inspection boreholes should be added to the working face head-on. The inspection boreholes should be located in the abnormal area of the working face or arranged parallel to the 0.5m position of the boreholes with 0.5>K₁ value>0.4, Δh₂>180, or S value>5kg.

Collect and measure the amount of drill cuttings for every 1 meter of drilling, and measure the S value. Measure the desorption indicators K₁ and Δh₂ of drill cuttings every 2 meters;

Determine the maximum amount of drilling cuttings S_{max} and the desorption indicators K_{1max} and Δh_{2max} for drilling cuttings.

4.1.2 Measures to prevent coal and gas outbursts in the working face

Advanced discharge drilling is selected as a local anti outburst measure for the working face. According to the test report on the effective discharge radius of different aperture discharge boreholes in the 3 # coal seam of a certain coal mine provided by Henan University of Technology, after 2 hours of discharge, the effective discharge radius of the φ75mm discharge borehole is 1.4m. As the discharge time increases, the discharge radius also increases. When

the discharge time is one shift (8 hours), the effective discharge radius of the discharge borehole can be appropriately increased by 0.1-0.2m. Therefore, 21 advanced discharge boreholes can be arranged on the working face to cover the entire section.

When the excavation face is predicted to be a dangerous outburst face, advance discharge drilling is performed to eliminate the risk of coal and gas outburst in the face. The advanced discharge boreholes are arranged in a fan-shaped pattern on the horizontal projection, with a borehole diameter of 75mm and a depth of 13-15m. The final drilling points of the two sides of the boreholes are controlled 5m outside the contour lines of the working face roadway. There are a total of 3 rows of boreholes arranged, with 7 boreholes in each row and a spacing of 0.80m between boreholes. The arrangement and depth of the boreholes in the front row can be arranged according to the actual situation on site. When the construction level of the roadway changes, the drilling arrangement will be adjusted. Only when the effect inspection does not exceed the standard can the footage be taken. Otherwise, supplementary anti outburst measures should be taken before the effect inspection.

When soft stratification occurs on the working face, a row of advanced discharge boreholes should be constructed with a thickness of less than 0.3m for soft coal; Construction of two rows of advanced discharge boreholes with a soft coal thickness of 0.3-0.5m; Supplementary anti outburst measures must be formulated and implemented for soft coal with a thickness exceeding 0.5m. The advanced discharge drilling hole has a diameter of 75mm, a depth of 15m, and a spacing of 0.4m between openings. The drilling holes are evenly arranged, and the final drilling point is controlled 5m outside the contour line of the working face roadway, mainly for coal mining.

When the predicted (including retesting) indicator K1 value exceeds the standard, advance discharge drilling will be carried out during construction. After 8 hours of discharge after completion of the advance discharge drilling, the inspection will be carried out again. If the inspection index is still greater than the critical value of the drilling chip index method, the discharge time shall be extended or local supplementary anti outburst measures shall be implemented until the inspection is qualified. When K1 and Δh_2 pass the test and the S value exceeds the standard, there is no need for emission time.

After the effectiveness inspection of the working face measures is completed, the 4 # detection borehole will be extended forward as an advanced borehole to detect the geological structure in front of the working face and observe the signs of protrusion. The advanced borehole diameter is 75mm, and the depth must exceed the approved excavation footage by no less than 10m.

4.2 On site tracking and measurement of prediction indicators

Through on-site inspection of the 1306 return air duct excavation working face in a certain coal mine, a total of 276 sets of K1 values (see Table 2), 88 sets of Δh_2 values (see Table 3), and 276 sets of S values (see Table 4).

Table 2 Statistical Table of K1 Value Distribution

A total of 276 times	K1 Value Distribution	Number of times	Proportion(%)
	0-0.10	9	3.26
	0.10-0.20	118	42.75
	0.20-0.30	83	30.07
	0.30-0.40	38	13.77
	0.40-0.50	20	7.25
	> 0.5	8	2.90

Table 3 Statistical Table of Δh_2 Value Distribution

A total of 88 times	Δh_2 Value Distribution	Number of times	Proportion(%)
	0-100	35	39.77
	100-120	12	13.64
	120-140	16	18.18
	140-160	9	10.23
	160-180	6	6.82
	180-200	2	2.27
	> 200	8	9.09

Table 3 Statistical Table of Δh_2 Value Distribution

	Δh_2 Value Distribution	Number of times	Proportion(%)
A total of 88 times	0-100	35	39.77
	100-120	12	13.64
	120-140	16	18.18
	140-160	9	10.23
	160-180	6	6.82
	180-200	2	2.27
	> 200	8	9.09

Table 4 Statistical table of S value distribution of drill cuttings

	S Value DistributionK1	Number of times	Proportion(%)
A total of 276 times	0-2.0	7	2.54
	2.0-3.0	179	64.86
	3.0-4.0	87	31.52
	4.0-5.0	3	1.09
	5.0-6.0	0	0
	> 6.0	0	0

4.3 Determination of sensitive indicators

Write an Excel calculation program to input the measured original data into the sensitivity functions of various indicators, and calculate $M1(i)$, $M2(i)$, and $M3(i)$. The calculation results are: $M1(i)=0.41$, $M2(i)=0.09$, $M3(i)=0.05$. From the calculation results, $M1(i)$ is much larger than $M2(i)$ and $M3(i)$. For the 3106 coal mining face of a certain coal mine, among the three indicators used for predicting outburst, the drill chip gas desorption index K1 is more sensitive than the drill chip gas desorption index Δh_2 and the drill chip amount S. The order of sensitivity of various indicators to coal and gas outbursts is: drilling cuttings gas desorption index K1>drilling cuttings gas desorption index Δh_2 >drilling cuttings quantity S.

Table 5 ensitivity analysis results of predictive indicators

Parameter	K1	Δh_2	S
Indicator sensitivity	0.41	0.09	0.05

5 Conclusion

By mathematical modeling, the measured gas desorption data of each drilling chip is dimensionless and standardized, and its sensitivity function is calculated to determine its sensitivity.

For the 1306 coal mining face of a certain coal mine, among the three indicators used for predicting outbursts, the gas desorption index K1 of drill cuttings is more sensitive than the gas desorption index Δh_2 and the amount of drill cuttings S.

According to the critical value of $0.5\text{mL}/(\text{g} \cdot \text{min}^{1/2})$ for the gas desorption index K1 of drilling cuttings, there have been 8 instances of exceeding the limit, and according to the critical value of $0.4\text{mL}/(\text{g} \cdot \text{min}^{1/2})$ for the internal control index of the mine, there have been 28 instances of exceeding the limit. In actual testing, when the K1 value is greater than the internal control value of $0.4\text{mL}/(\text{g} \cdot \text{min}^{1/2})$, abnormal phenomena such as spraying holes, sticking drill holes, abnormal gas emission from drilling holes, or coal cannon firing may occur during drilling. Moreover, the larger the K1 value, the more obvious the dynamic phenomenon. When local anti outburst measures are taken to discharge the drilling holes, the K1 value decreases significantly, so it can be concluded that the K1 index is more sensitive, which is consistent with the conclusion drawn from the mathematical analysis method above.

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