Applications of online integrated system for coal and gas outburst prediction: A case study of Xinjing Mine in Shanxi, China

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Abstract
In this study, an indicator model and system for coal and gas outburst prediction are identified and established based on gas geological anomalies, mining stress, and gas emission characteristics. In this regard, the coal and gas outburst prevention techniques and mine rules in China are taken into account. In addition, using this model, an online integrated system and database for coal and gas outburst prediction were built for Xinjing Mine in Shanxi Province. The application results of the prediction system indicate that the system software and hardware can guarantee early warning of coal and gas outburst. The system is continuous and stable, and the early warning results are issued in a timely and accurate manner. The accuracy of the early warning results is high and consistent with the actual risk of the mine.

Keywords
case study, coal and gas outburst, coal mine, multisource information, prediction

1 | INTRODUCTION

Coal and gas outburst accidents have been among the most serious disasters affecting coal mine production and often cause the most serious damages or secondary disasters.¹² This is especially true in the complex geological conditions of China’s coal seams. Furthermore, with increasing depth and intensity of mining, the gas content and gas pressure are continuously increasing, exacerbating the risk of outbursts.³ The first step in coal and gas outburst prevention and control is to judge the probability and intensity of outbursts based on the prominent precursor information. The accuracy of forecasting and early warning systems plays a crucial role in the prevention and control of outburst accidents.

Coal and gas outbursts are complex dynamic disasters, which, based on a comprehensive supposition, result from interactions among the structural mechanical properties of coal, ground stress, and gas pressure.⁴ In addition, coal and gas outbursts are closely related to geological structure, adsorption characteristics, and other factors.⁵-¹² Through protracted and unremitting efforts, researchers from several countries have advanced various outburst prediction methods based on the understanding of outburst mechanisms.
Outburst risk prediction can be roughly divided into the contact static prediction method, noncontact dynamic prediction method, and multisource information comprehensive prediction method. The major prediction method in the Prevention Regulations of Coal and Gas Outburst (called Regulations hereafter)\textsuperscript{13} prescribed by China in 1995 and Rules of Preventing Coal and Gas Outburst (edition asking for opinion, 10, 2008) is classified as a contact static prediction method. Both regulations stipulate that coal’s damage style, initial rate of methane diffusion $\Delta p$, consistent coefficient of coal $f$, and seam gas pressure $p$ should be taken as foundation indices of coal seam outburst prediction. Additionally, regional prediction should be based on geological statistical methods and the comprehensive indices ($D$, $K$), which, along with desorption indices for drill cuttings ($h_2$ or $K_1$), should be selected for outburst prediction at the cross-cutting coal face. The initial gas emission velocity from drill holes ($q_{em}$), the $R$ value index method, and desorption indices for drill cuttings (including $h_2$ or $K_1$ and the volume of cuttings $S$) should be used at the coal heading face and mining face. This traditional coal and gas outburst prediction is an empirical sampling-based, discontinuous, and localized prediction method, which cannot fully meet the needs of high-yield, high-efficiency mine safety production. The noncontact dynamic prediction method is the method for assessing outburst risk by monitoring the physical properties of sound, electricity, magnetism, and thermal and gas emission in the initiation process of coal and gas outburst, including the AE acoustic emission signal,\textsuperscript{14-17} electric radiation detection,\textsuperscript{18,19} gas emission,\textsuperscript{20,21} and microseismic monitoring methods.\textsuperscript{22,23} These methods are dynamic and continuous in time and space, and only require minimal work. Further, they do not occupy special working time or affect production. Liang et al\textsuperscript{24} studied the relevant influence factors for the prediction method based on initial expansion energy of the released gas. The roles of gas pressure and gas adsorption in coal and gas outbursts were also studied.\textsuperscript{8,25}

However, a certain forecasting indicator can only indirectly and partially reflect a certain aspect of the risk and not risk from multiple directions. Multisource information comprehensive prediction of outbursts or multisource information artificial intelligence prediction uses a series of representative indicator systems screened from two former prediction methods, which are then analyzed by an artificial intelligence system to predict coal and gas outbursts. Recently, scholars have adopted the comprehensive evaluation (CE) method, the gray theory prediction (GTP) method,\textsuperscript{26} the fuzzy logic comprehensive appraisal (FLCA) method,\textsuperscript{27} and the artificial neural network (ANN) method\textsuperscript{28-30} to develop outburst prediction indices. Xie et al\textsuperscript{30} established a new coal and gas outburst prediction model that consists of four levels and fourteen factors that combined the improved fruit fly optimization algorithm (IFOA) and the general regression neural network (GRNN) algorithm to establish an IFOA-GRNN prediction model.

The multisource information comprehensive prediction method is in alignment with the current trend of informatization and intelligent development of coal mines and is the development direction of coal and gas outburst prediction and early warning technology. Therefore, this work studies the Xinjing Coal Mine and, based on the mine production process, geological data, and more than 200 historical gas-dynamic phenomena, comprehensively analyzes the multisource information to build a comprehensive early warning indicator system and coal mine model. The aforementioned multisource information includes gas geology, mining influence, daily forecast, gas emission, mine pressure, and antiburst measures. Further, using this model, an online integrated system and database were built to predict coal and gas outbursts, and to achieve real-time monitoring and intelligent identification of the outburst danger of the working surface.

\section{Indicator System and Model for Coal and Gas Outburst Prediction}

The research on indicator systems and models for coal and gas outburst prediction is the premise and foundation of prediction implementation. Based on the analysis of outburst accidents in recent years, there are two basic events that cause coal and gas outbursts: One reflects the objective and outburst danger of the working face, such as the mechanical properties of the coal seam, the occurrence of gas, the geological structure, and the concentration of mining stress; the second reflects events related to major defects in the antiburst measures, such as the absence of forecast implementation (effectiveness inspection) and nonstandardized prediction (effective inspection) in drilling construction. These incidents are the sources of danger that cause coal and gas outbursts, and form the main basis for early warning. Therefore, based on the mine production process and historical gas disaster characteristics, a comprehensive early warning system index system based on six informational aspects including gas geological, mining effects, daily prediction, gas emission, ground stress, and prevention measures was constructed, as shown in Figure 1.

Meanwhile, the value of each indicator was determined based on historical outburst accidents and single-factor indicator values (Table 1). For the indicators described in the Regulations,\textsuperscript{13} we directly used their critical values to determine values such as the firmness coefficient of coal $f$ and the mining impact range. For other indicators that are not clearly specified, based on the data of more than 200 gas-dynamic phenomena in the Xinjing Mine, a preliminary analysis of the relationship between dynamic phenomena and indicators was
performed. The relationship between the coal seam gas pressure $p$ and the gas desorption index $K_1$ was then experimentally analyzed to obtain the $K_1$ critical value. Subsequently, the critical index of each basic event prediction index could be determined by building the correlation between the $K_1$ value index and each basic event.

### 2.1 Gas geology

Research indicates that over 90% of significant outbursts have been concentrated in strongly deformed zones along the axes of geologic structures.\textsuperscript{5,31,32} The prediction of the outburst area based on gas geology division theory suggests that the geological structure is the dominant geological factor controlling the outburst. The thickness of the soft coal and the gas content of the coal seam are the main gas geological indicators for the prediction of the outburst area. The geological structure controls the outburst by controlling the occurrence of gas, the type of coal structure, and the structural stress state.

Coal and gas outbursts always occur within a certain range of coal levels.\textsuperscript{33} The firmness coefficient of coal $f$ is generally less than 0.5 and is referred to in geology as “constructed coal” or “soft stratification.” According to the statistics of the $f$-values of the 80 outburst accidents recorded in Xinjing Mine over the years, it was found that the value of $f$ near the outburst location was relatively small (maximum of 0.57 and minimum of 0.34), among which 57 occurrences of $f < 0.5$ accounted for 71.25% of the total. This indicates that tectonic coal has a large influence on outbursts.

Table 2 shows an example of the historical influence of coal thickness variation. It can be seen that when the coal thickness growth rate was less than $-25.0\%$ (the coal seam thinned), an outburst accident was likely to occur. This is because when the thickness of the coal seam changed, especially where the coal seam thinned, the state of the coal body stress also changed, and the gas pressure gradient increased, thereby increasing the risk of working face outbursts.

As the depth of burial of coal seams increased, the proportion of methane increased and the gas content increased. The first outburst location was at a depth of 390 m in Xinjing Coal Mine, and more than 80% of the gas outbursts occurred in mining faces deeper than 430 m. Moreover, as the depth increased, the intensity of gas outburst increased, which was manifested by a significant increase in the average and maximum gas emissions, as shown in Figure 2.

According to the statistics of coal and gas outburst accidents occurring in Xinjing Mine over time, it is found that 60% of the outbursts are related to geological structures (including faults, erosion zones, and syncline structures), as shown in Figure 3. This means that within a certain
distance from the geological structure, the risk of outburst increases.

2.2 Mining effects

Mining activity destroys the stress balance of the original rock, causing the redistribution of stress inside the rock mass, thus forming a stress concentration zone. When the working face of the outburst coal seam is in the stress concentration zone caused by mining, there is a large potential outburst danger. Measures must be expeditiously taken to eliminate the danger. To determine the relationship between the mining effects’ warning indicators and the outburst hazard levels, it is necessary to analyze the mining impact ranges of the adjacent strata, the coal seam, and the working face of the cross-drift to determine the distance between the early warning working face and its stress concentration zone.

1. Determination of influence range of adjacent layers

| Time       | Locations                      | Thickness in outburst location | Normal coal thickness | Growth rate of coal thick |
|------------|--------------------------------|--------------------------------|-----------------------|--------------------------|
| 2008.8.9   | Lunan 7206 working face        | 1.8                            | 2.5                   | −28.0%                   |
| 2008.9.27  | Lunan 7206 working face        | 1.8                            | 2.5                   | −28.0%                   |
| 2009.3.24  | North sixth lane, Lunan District 2 | 2.0                          | 2.6                   | −23.1%                   |
| 2009.3.25  | North sixth lane, Lunan District 2 | 1.8                          | 2.6                   | −30.8%                   |
| 2009.4.2   | North sixth lane, Lunan District 2 | 1.6                          | 2.6                   | −38.5%                   |
| 2009.4.3   | North sixth lane, Lunan District 2 | 1.6                          | 2.6                   | −38.5%                   |
| 2010.6.18  | Lunan 7204 tail lane           | 1.5                            | 2.0                   | −25.0%                   |

The influence of mining in the adjacent layer mainly considers the coal body stress concentration transfer in the mining space to the deep part of the bottom plate. After the mining face is recovered, with subsidence and collapse of the overlying strata in the goaf, the coal pillar is subjected to a large load, the stress concentration factor is significantly higher than the initial stress field, and the stress propagates to the coal seam floor rock layer, resulting in internal stress in the rock layer. Different degrees of stress increase and decrease have a great impact on coal mining activities. The protective range of the protective layer and the influence zone of the coal pillars are mainly determined by the pressure relief angle and the coal seam distance. This study mainly refers to the pressure relief angle data given in the Regulations and determines the protection range of coal seams and the influence range of coal pillars accordingly.

2. Determination of the influence range of mining in the coal seam
After roadway excavation, the original stress balance state of the coal and rock mass is disrupted. There are three areas of the pressure relief, concentrated stress, and original stress zones in the coal surrounding the roadway. The impact range of the roadway can be calculated according to Equation (1):

$$L_1 = 12R$$  \hspace{1cm} (1)

where $L_1$ is the radius of the roadway stress influence zone, and $R$ is the circumscribed circular radius of the roadway. The circumscribed circular radius of the Xinjing coal roadway is 2.5 m, and therefore, the radius of the affected area on both sides is 30 m.

The stress distribution of the coal around the mining area is related to various factors such as the mining area size, the original rock stress, the coal and rock layers' mechanical properties, mining process, and the roof management. Based on experience, the influence range of the support pressure in front of the mining face, the fixed bearing pressure in the inclined direction, and the supporting pressure in the rear goaf are not more than 60 m, 30 m, and 30 m, respectively.

3. Determination of the influence range of cross-drift working face

According to the requirements of the Regulations, before the uncovering coal mining face is drilled to a minimum normal distance of 10 m from the coal seam (when geological conditions are complex, it should be before 20 m), the geological structure, coal seam presence, and gas should be detected by pre-exploration drilling. The uncovering operation utilizes the minimum normal distance of 5 m from the top (bottom) plate of the outburst coal seam to 2 m (minimum normal distance) through the coal seam into the top (bottom) plate. Therefore, for cross-drift uncovering coal, warning information should be provided within the range of 10 m from the normal distance of the coal seam to 2 m from the top (bottom) plate of the coal seam, as shown in Figure 4.

2.3 | Daily prediction

The daily forecasting early warning indicators in Xinjing Coal Mine mainly include the drill cuttings' gas desorption index $K_1$ and the drilling power phenomenon, which includes regional effective inspection and nozzle holes and suction drills that appear during drilling construction. Lei obtained $K_1$ and $p$ as a power function through a large number of experiments (153 samples in different regions in China). Four of coal sample groups were collected from four different locations in the 3 # coal seam for testing, and the same power function relationship was obtained, as shown in Figure 5. Therefore, the fitting threshold of $K_1$ can be obtained by substituting the gas pressure threshold value of 0.74 MPa given by the Regulations into the $K_1 – p$ relationship (Equation 2) established by the experiment. The values for Xinjing Mine are shown in Table 3.

$$K_1 = ap^b$$  \hspace{1cm} (2)

where $a$ and $b$ are the fitting constant.

By analyzing the variation characteristics of $K_1$ near the geological structure of multiple lanes, it is found that all structures have a certain control range. When the working face enters this range, the $K_1$ value often exceeds the standard. Through comparison and analysis of the measured $K_1$ value and different structural locations, the fault control range is generally not more than 15 m, as shown in Figure 6. By 20 m from the edge of the erosion zone, $K_1$ frequently

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Schematic diagram of the process of uncovering coal of cross-drift}
\end{figure}
exceeds the standard; therefore, the control range of the erosion zone in Xinjing Coal Mine is determined to be 20 m outside the edge, as shown in Figure 7. $K_1$ exceeded the limit within 30 m from the synclinal axis in the south third lane, in the Baoan District, as shown in Figure 8. Therefore, the influence range of the synclinal structure is determined to be within 30 m of both sides of the shaft.

Outburst accidents often occur in soft stratification areas, which are inseparable from the causes of soft stratification. The formation of soft stratification is closely related to the geological structure and is formed under the action of tectonic stress, which causes the coal body first to deform and then rupture. As the crack expansion deepens, the coal body is gradually divided into granules, during which smaller particles are formed due to friction, extrusion, and enthalpy between the two, until they become fine powder. The entire formation process of soft stratification not only makes the relatively hard coal body soft and brittle, but also accumulates a large amount of gas, which are factors that favor outbursts. It is found that when the soft stratification thickness reaches 0.3 m or more, $K_1$ frequently exceeds the standard, as shown in Figure 9.

2.4 Mining pressure

The main role of stress in outbursts is that it can destroy the coal body, as well as change its physical properties such as pore fracture structure, desorption characteristics, and permeability characteristics. This causes the adsorbed gas in the coal body to desorb in large amounts, causing the gas pressure to rise sharply, thereby providing the energy source for accelerating outburst development.

Figure 10 shows the variation curves of typical mine pressure and $K_1$ values. It can be seen that the two show good consistency. The correlation analysis method is used to quantitatively analyze the pressure warning thresholds, which were 43 MPa and 55 MPa, respectively. According to the principle of maximum safety, 43 MPa is taken as the critical mine pressure warning value; however, it should also be recognized that the linear fitting method is approximate, and its accuracy is significantly affected by the correlation between the $K_1$ and mine pressure values. Therefore, increasing daily observations of mine pressure characteristics as an auxiliary indicator for the mine pressure threshold warning may improve the accuracy of the early warning system, because the mine pressure manifestations (such as the roof subsidence and bottom drum) are the result of mine pressure, which largely reflect the working face mine pressure.

2.5 Comprehensive analysis model for coal and gas outbursts

Through the analysis of the coal and gas outburst causes, a comprehensive analysis model for coal and gas outbursts is established according to the principle of multifactor and multiple indicator comprehensive early warning (Figure 11). The outburst early warning levels are divided into two categories: state early warning and trend early warning, and each category is divided into different levels, as shown in Table 4.

During production, the value of each early warning indicator reflects the status of the early warning elements of the work surface. When highlighting the early warning, according to the indicator values in the early warning indicator system, and to the corresponding early warning rules in the early warning rule database, the corresponding primary warning results can be obtained, and then, the secondary warning results are obtained from the primary warning. Based on the comprehensive early warning results, the principle of the highest level and the principle of missing values are always followed throughout the early

| TABLE 3 | Indicator thresholds for Xinjing Mine |
|----------|-------------------------------------|
|          | Group 1  | Group 2  | Group 3  | Group 4  | Mean     |
| Fitting constant $a$ | 0.5029  | 0.5621  | 0.5944  | 0.5455  | /        |
| Fitting constant $b$ | 0.6695  | 0.6475  | 0.5948  | 0.6389  | /        |
| $R^2$      | 0.9975  | 0.9979  | 0.9961  | 0.9968  | /        |
| $K_1$ indicator thresholds | 0.41  | 0.46   | 0.50    | 0.45    | 0.455    |
warning process. The most advanced principle is when the final warning result is determined by the primary warning result, the highest warning level and the highest risk in the primary warning result are taken as the final result. The missing value principle refers to the determination of the final warning result when determining it from the primary warning result without affecting the lack of primary warning results and early warning indicators. Owing to the many influencing factors on coal and gas outbursts, not all factors are involved in a gas outburst accident, and not all signs will appear. This is reflected in the lack of early warning indicators in the early warning process; therefore, the absence of certain indicator values cannot affect the determination of early warning results.

3 | ONLINE INTEGRATED SYSTEM FOR COAL AND GAS OUTBURST PREDICTION

3.1 | Key points

The design principles of the system are as follows:

1. Each subsystem database is used to store the necessary data used by the system and can still be used normally without using the comprehensive early warning database, which can reduce the data access time and improve the operation response speed. The comprehensive early warning database is the intersection of each subsystem.
databases, storing the basic management information and the professional information required for early warning collected from each subsystem, such as geological survey, gas geology, mining operations, outburst prevention, ventilation gas, gas monitoring, mine pressure monitoring, and other data.

2. The subsystem can be disconnected from the network during operation, and all functions can be completed using only the local database. After modification or maintenance is completed, the data are synchronized with the early warning database.

3. Because geological survey, gas geology, gas emission, and comprehensive early warning servers may modify spatial data, a subsystem needs spatial data collected and calculated by other subsystems requiring two-way synchronization. However, some spatial data can be unidirectionally synchronized.

4. According to the user's requirements for the software system and the software system requirements for the hardware system, the system determines which subsystems use the C/S structure and which use the B/S structure. Geological survey, gas geology, mine pressure, and

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**FIGURE 7** The relationship of erosion zone and $K_1$ value in south fourth lane, Baoan District

(A) 200 m footage

(B) 600 m footage
gas emission subsystems have higher requirements for spatial data access and require fast results. Therefore, C/S structure should be adopted and the local database system should be adopted. The mining progress, comprehensive early warning management platform, and the comprehensive query system for early warning results require access to the latest data and are closely related to the comprehensive early warning database. Therefore, the B/S structure can be adopted or directly connected to the C/S structure of the comprehensive early warning database.

5. In the system architecture design, common subsystem division schemes are based on the business process stage, discipline specialty, and organization of general coal mine enterprises. According to the organizational structure of general coal mine enterprises, not only the professional factors of the discipline, but also the characteristics of the business management process are considered, which is beneficial to ensure that the data required by the system can be collected accurately and timely, and is also beneficial to the organization of modeling designers and developers. Therefore, division according to the organization of general coal mining enterprises is the most feasible design.

3.2 | System structure

The early warning system server is placed in the network center room of the Xinjing Mine and is connected to the KJ90 gas monitoring data server of the ventilation dispatching machine room through the local area network to directly collect the real-time gas monitoring data. The client computers are distributed in various departments such as the antiburst office and the geodetic department. The physical structure of the system is shown in Figure 12.

The logical structure of the system refers to the logical operation structure that is displayed when the software system is running. The software system is centered on the spatial database of the early warning system, with the early warning processing module as the core, based on geological survey management, mining progress management, antiburst information dynamics, gas geological analysis, gas emission analysis, mine pressure analysis, and early warning information platform.

3.3 | Subsystems and database

Based on full consideration of coal mine organization and structure, the geological survey management, gas geological dynamic analysis, outburst dynamic management and analysis, gas emission dynamic analysis (KJA), and mining pressure monitoring and early warning systems were constructed as subsystems. In addition to the daily management work of each functional department, each subsystem also provides corresponding basic data for the comprehensive early warning system. For example, the geological survey management system provides basic data for comprehensive early warning analysis, such as the location and basic mining parameters of the outburst prevention working face, the mining deployment in the adjacent space, geological structure information, and geological drilling information. The early warning system calculates and checks the spatial position relationship of the working surface based on these data. The comprehensive outburst early warning platform mainly customizes early warning rules and index parameters, and queries, analyzes, and issues early warning information.

The coal and gas outburst warning system is a complex system formed by the organic combination and coordinated operation of multiple subsystems. During the operation of the early warning system, the subsystems are distributed in different functional departments and are in different spatial locations. Data sharing, processing, and output of each subsystem are highly shared; however, each has its own emphasis. Therefore, the dynamic security information database is designed to be distributed. The database (DDB) storage structure makes it easy to use and minimizes data redundancy and confusion.

The dynamic security information database needs to store spatial object data with dual characteristics of space and attributes such as coal seam gas occurrence, well engineering, and geological structure, and also needs to use nonspatial object data such as mining progress, anti-burst measures, daily prediction, and mine monitoring data. Therefore, the dynamic spatial information database design uses a relational data model.

Based on the data flow analysis of each subsystem, combined with the responsibilities of various departments on the coal mine site, the dynamic security information database structure is designed, and the corresponding database is divided into six subsystem databases of comprehensive early warning.
warning, geological measurement, gas geological, dynamic defense databases, mine pressure database, and gas emission dynamic characteristic databases, which store the necessary data used by the subsystem, thereby reducing the data access time of each subsystem and improving the operational response speed. The integrated early warning database is the intersection of several other subsystem databases and stores the basic management information collected from other subsystems and related professional information required for early warning.

1. Comprehensive early warning database

The integrated early warning database is the intersection of several other subsystems, and the stored information includes a public relationship table, basic space data, and various subsystem information tables. According to the physical type and usage difference of the basic spatial data, it is divided into three types: ground, underground noncoal and coal seam, and the basic spatial feature set as established accordingly.

2. Geological Survey Database

The geological survey database mainly stores the geodetic data required by the geological survey management subsystem and provides basic spatial coordinate information for the integrated early warning system. It uses SQL Server 2008 Express as a database management system and exchanges data with a comprehensive alert database through data synchronization.
3. Gas Geology Database

The gas geological database mainly stores the coal seam occurrence information, geological exploration, gas drainage, and basic gas parameters (pressure, content, gushing amount, etc) required for the operation of the gas geological analysis subsystem and highlights the dangerous area division. It is synchronized with the comprehensive early warning database for data exchange and provides gas geological information.

4. Antiburst dynamic database

The antiburst dynamic database mainly stores the antiburst measures' design information, daily prediction (effective inspection) drilling construction and index measurement information, antiburst measures' construction information, and antisurge construction map information, and synchronizes real-time data transfer through the interface and comprehensive early warning database.

5. KJA database

The KJA database is used to store sensor information sampled from the gas monitoring database, gas monitoring
information, and monitoring data analysis results, and maintain real-time synchronization with the comprehensive early warning database through the interface.

6. Mine pressure database

The mine pressure database is used to store mine pressure monitoring information and mine pressure observation index information, as well as time and space information of working face mining, and maintain real-time synchronization with the comprehensive early warning database through the interface.

### Table 4

| Categories             | Levels | Description                                                                 |
|------------------------|--------|-----------------------------------------------------------------------------|
| State early warning    | Normal | Various indicators on the working face are normal and can be operated safely |
|                        | Warning| There is no danger in the prediction of the working face, but it needs to focus on and strengthen management |
|                        | Danger | The working face has an outburst danger, and the operation needs to be stopped and preventive measures or further confirmation of the prominent danger needs to be taken |
| Trend early warning    | Green  | The outburst danger ahead moves toward safety                                 |
|                        | Orange | There may be danger at a certain distance ahead; please pay attention            |
|                        | Red    | The outburst danger ahead is becoming serious and should focus on strengthening management and measures |

## 4 | Applications of the Online Integrated System

### 4.1 | Overviews of the workface

The Xinjing Mine is located west of Yangquan City, Shanxi Province, 18 km from the city center. The coal seams in the well fields are stable in storage and are all high-quality anthracite. The mine adopts a mixed method of main inclined shaft and auxiliary vertical shaft extraction. The whole minefield is divided into two zones, south and north, with a total...
of four districts, namely, the Fowa, Baoan, Lunan, and Lubei districts. There are two mining levels in the mine. The current mining level is +525, and 3 #, 8 #, and 15 # coal seams are the primary mining targets. The absolute gas emission of the Xinjing Mine is 288.28 m³/min and the relative gas emission is 27.49 m³/t, which classifies the mine as a coal and gas outburst mine. In addition, the 3 # coal seam is an outburst coal seam.

The lanes in the 3 # and 8 # coal seams were selected as analysis objects. The average distance between the two coal seams is about 48 m. The histogram of the coal seams and rock is shown in Figure 13. The south eighth lane is located in the middle of the south wing of the second Lunan District. The 3 # coal seam in this area is stable (coal thickness is approximately 2.34 m-3.05 m and averages 2.56 m, and the structure is simple). The coal seam is mainly composed of high-quality anthracite with low ash and low sulfur, mirror coal and bright coal, and endogenous fissures. The southern part of south eighth lane is a monoclinal structure with a tendency to SE, and the dip angle of the coal seam is 3°-6°. The middle area is an anticlinal structure with one NW axis, and the dip angle of the two limbs is 2°-5°. The north is a monoclinic structure with a tendency to SE, and the dip angle of the coal seam is 3°-10°.

The 7212 cut lane is located in the middle of the north limb of the second Lunan District. The 3 # coal seam in this area is stable and has a simple structure. It is also high-quality anthracite with medium ash and low sulfur. The coal seam is mainly composed of mirror coal and bright coal, and endogenous fissures develop. The area where the 7212 cut lane is located is a monoclinal structure with a tendency to SE. The dip angle of the coal seam is 3°-11°. The north is adjacent to a flushing belt, which may affect the outstanding danger of the whole driving face.

The north sixth auxiliary lane is located in the eastern part of the north limb of the first Lunan District. The 8 # coal seam in this area is stable and has a simple structure. It is anthracite with medium ash, medium sulfur, and medium phosphorus content. The coal seam is mainly composed of semibright coal and develops endogenous fissures. The south of the north sixth auxiliary lane is an anticlinal structure with a NE-trending axis. The inclination angle of the two limbs is 2°-7°. The middle part is an oblique structure with an axis almost WE; the inclination angle of the two limbs is 2°-6°. The north is a monoclinic structure with a tendency to W, and the inclination angle is 3°-5°.

Inspecting the prominent hazard predictions in the working face area, the gas content index is adopted, and the critical value of the index is 7 m³/t. The regional antiburst measures of coal seam gas with pre-extracted coal roadways are used to determine the propulsion degree according to the actual construction depth of the main hole. The advanced reserve distance is not less than 20 m; the regional measure effect test uses the gas content index, and the index critical value is 7 m³/t. The work surface prediction method is used for regional verification. The K₁ and S indicators are used for the prediction of the working face. The threshold values of the indicators are 0.4 mL/g min⁻¹/² and 6 kg/m, respectively. The prevention measures for the face are used for local discharge holes, and 7 m measures are reserved for advancement. The working face predicts the same indicators and thresholds.

4.2 Results of the system prediction

According to the relevant data provided by the antiburst and geological departments, there were two major outburst risks in south eighth lane during the inspection period. One appeared on February 2, when the predicted K₁ value reached 1.28 mL/g min⁻¹/², and the soft layer thickness was 0.8 m. The other appeared on March 11, revealing a normal fault with a drop of 0.8 m.
At midnight on January 30, the trend pre-alarm stage was get as “orange”; at 4:00 on February 1, the trend warning was upgraded to “red”; and at 8:00 on February 2, the status warning was upgraded to “dangerous” and the trend warning was “orange.” When the $K_1$ forecast exceeded the standard, the triggering factor of this early warning process was gas emission (Figure 14). The warning result was accurate, and it had a good advance prediction (2 days ahead of the $K_1$ prediction). In addition, on February 2, the soft stratification thickness exceeded the warning threshold of 0.3 m, and the early warning system gave a state of “warning” from the gas geological aspect, reminding relevant departments to strengthen protection.

At 8:00 on March 7, the trend pre-alarm was “orange,” and the triggering factor was gas geology, indicating that the distance of the working face from the structural influence range was within 10 m, and the trend warning of 8:00 on March 10 upgraded it to “red” and the state warning to “warning.” This indicated that the working face entered the structural influence range (as shown in Figure 15), and the structure would be revealed. By the beginning of the midnight hour on March 9, the early warning system gave an “orange” warning from gas emissions, and at midnight on the 1st, it was upgraded to a “red” warning, indicating that gas emissions emerged abnormally under the influence of geological structures. The early warning process warns of outburst dangers in front of the working face from the aspects of gas geology and gas emission. The characteristics of outburst hazards are completely consistent with the theoretical research and the situation on the site, which further demonstrates that the early warning system is predictive and reliable.

The magnitude of the danger in the working face is related to various factors such as gas geological conditions, antiburst measures, and mining deployment in the area where the working face is located. The comprehensive early warning results judge the outburst danger at the working face from different perspectives and count the various working faces through statistics. The difference in the proportion of different levels of early warning results during excavation can reflect the overall danger risk of the working face. Meanwhile, by comparing the distribution of various early warning indicators on the same working face, the risk-sensitive indicators of the working face can be reflected.

The comparative analysis of the early warning effect takes the 3 # coal seam south eighth lane, 7212 cut lane, and the 8 # coal seam north sixth auxiliary lane as examples. By comparing the proportion of the early warning results of different levels of each working face, we tested whether the magnitude of the outburst hazard of early warning result and actual working face is consistent.

The results can be seen from Figure 16. First, the early warning result level of the north sixth auxiliary lane is obviously lower than that of the south eighth lane and 7212 cut lane. This is completely consistent with the actual situation, because the overall deterioration of 8 # coal seam is lower than that of the 3 #, and the gas content is less than the 3 # coal seam. In addition, the pressure relief effect of the upper 3 # coal mining on the lower coal seam in the upper part of the north sixth lane greatly reduces the

| Strata            | Lithology        | Thickness |
|-------------------|------------------|-----------|
| 2# coal seam      | Sandy mudstone   | 0.05      |
|                   | Coarse sandstone | 3.72      |
|                   | Sandy mudstone   | 3.32      |
| Kaolinite mudstone| 3# coal seam     | 2.56      |
|                   | Sandy mudstone   | 4.90      |
| 4# coal seam      | Sandy mudstone   | 4.85      |
|                   | Medium-grained   | 7.71      |
|                   | sandstone        |           |
| Mudstone          | 6.33             |
| 8# coal seam      | Sandy mudstone   | 5.00      |
|                   | Medium-grained   | 8.15      |
|                   | sandstone        |           |

FIGURE 13 The histogram of coal seam and rock
outburst danger of the driving face of the north sixth auxiliary lane. Second, the warning level of the south eighth lane is lower than 7212 cut lane, which is also consistent with the actual situation. The 7212 cut lane is located at the edge of the scouring structure belt, and the outburst danger of the working face is greatly affected by the scouring belt. Although the 7212 cut lane working face adopts more intensive antiburst measures and maintains a small tunneling speed, there are still two large $K_1$ values exceeding the standard during the inspection, and the maximum reaches...
1.73 mL/g min$^{1/2}$. This indicates that the 7212 cut lane does have a serious outburst danger. It can be seen that the early warning results are consistent with the actual danger risk at the working face, which reflects the overall risk of different working faces.

5 | CONCLUSIONS

1. The regularity of coal and gas outburst, geological conditions, characteristics of mining deployment, and outburst prevention technology in Xinjing Mine over the years are statistically analyzed. Based on the measured data from the underground, the impact of gas geological, mining effects, daily prediction, gas emission, mining pressure, and methods of preventing the outburst danger of working face in Xinjing Mine were analyzed. The relationship between various factors and the evolution characteristics of outburst dangers was established. Finally, an online comprehensive analysis and early warning index system and rules for coal and gas outburst specific to Xinjing Mine were established.

2. Based on the indicator system and model, combined with the daily prevention management at Xinjing Mine, the geological survey management system, and the professional subsystems such as the gas geology dynamic analysis system, antburst dynamic management and analysis system, and gas emission dynamics analysis system, the mining progress management, and the mine pressure monitoring and early warning systems, as well as the gas outburst comprehensive early warning platform, have been adaptively adjusted. In addition, a new comprehensive early warning software system for Xinjing Mine has been established, which has achieved its comprehensive risk analysis and early warning function.

3. The application effects of the prediction system were investigated. The results show that the system can guarantee early warning. The system is continuous and stable, and the early warning results are issued in a timely and accurate manner. The accuracy of the early warning results is high and consistent with the actual risk of the working face.

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