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Research and Development and On-site Application of Intelligent Early Warning System for Coal and Gas Outburst

Yong Diao [1, 2]

[1] China Coal Technology and Engineering Group, Chongqing Research Institute, Chongqing 400037, China

[2] State Key Laboratory of Coal Mine Disaster Prevention and Control, Chongqing 400037, China

Abstract

To address the challenge of early warning for coal and gas outburst disasters, taking Shanxi Xinjing Mine as the research context and based on the statistical analysis of 209 gas dynamic phenomena in the mine, an early warning indicator system covering three dimensions—production system, region and working face—was constructed. A multi-source information fusion early warning model based on association rules and evidence theory was developed, integrating four core modules: monitoring and data collection, professional analysis, early warning dissemination, and database management. This culminated in the formation of an intelligent early warning system for coal and gas outbursts. Field application results demonstrate that the early warning model exhibits self-learning and self-evolving characteristics. During the evolutionary improvement phase, the overall accuracy of early warnings for heading working faces increased from 81.78% to over 91%, while the overall accuracy for mining working faces remained stable at over 91%. In the early warning application phase, the system achieved an overall early warning accuracy of 91.52%, with a 0% rate of missed reports for non-outburst hazards and an 8.54% rate of false reports for non-outburst hazards, enabling precise early warning of outburst disasters and providing technical support for safe coal mine production.

Keywords

Coal and Gas Outburst; Intelligent Early Warning; Indicator System; Multi-Source Information Fusion; Field Application.

1. Introduction

Coal and gas outburst is a typical dynamic disaster during coal mining, characterized by suddenness, violence, and destructiveness, posing a severe threat to mine safety and the lives of personnel [1-2]. As coal mining depth increases, gas pressure in coal seams and geostress rise significantly, further exacerbating the risk of coal and gas outbursts, which has become a key factor restricting the safe and efficient exploitation of coal resources in China [3-4].

Currently, early warning for coal and gas outbursts primarily relies on single indicators or empirical judgment, leading to issues such as delayed warnings and low accuracy. Despite extensive research by scholars both domestically and internationally on outburst mechanisms and early warning technologies, the complexity of outbursts—due to their coupling with multiple factors such as geological structures, gas occurrence, and mining disturbances—renders precise early warning a persistent challenge in the industry [5-8]. Based on this, taking Xinjing Mine of Yangquan Coal Industry Group as a demonstration mine, research and development of an intelligent early warning system for coal and gas outbursts, along with its field application, were conducted. Through multi-source information fusion and intelligent

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algorithms, early identification and precise early warning of outburst risks were achieved, providing technical references for similar outburst-prone mines.

2. Mine Overview and Outburst Characteristics Analysis

2.1. Basic Mine Information

Shanxi Xinjing Mine Coal Industry Co., Ltd. is located in the northwestern part of Yangquan City, 8 km from the city center, and falls under the administrative jurisdiction of Yangquan City. The mine was originally the new pit of Yangquan Mining Bureau's No. 3 Mine, with construction commencing in 1990 and production starting in 1997. It was restructured as a subsidiary of Yangquan Coal Industry Group in 2009. The mine possesses all necessary "three certificates and one license," with a mining permit authorizing a production scale of 5.8 million tons per annum and a mining area of 64.75 km^2, valid until March 2038. The safety production license approves a production capacity of 3.78 million tons per annum, with mining operations targeting coal seams No. 3, No. 8, and No. 15.

The coal-bearing strata within the mining area primarily consist of the Upper Carboniferous Taiyuan Formation and the Lower Permian Shanxi Formation, containing a total of 15 coal seams with a combined thickness of 20.85 m and a coal coefficient of 11.73%. Coal seams No. 3 and No. 15 are stable and minable, while coal seam No. 8 is relatively stable and mostly minable; all are outburst-prone coal seams. The mine employs a combined main inclined shaft-auxiliary vertical shaft development method, with zonal ventilation and mechanical exhaust ventilation, achieving a total intake air volume of 45,545 m^3/min and a total return air volume of 46,095 m^3/min, classifying it as a mine with easy ventilation conditions. In 2017, the mine's absolute gas emission rate was 214.86 m^3/min, with a relative gas emission rate of 30.95 m^3/t, designating it as an outburst-prone mine.

2.2. Characteristics and Patterns of Coal and Gas Outbursts

Through statistical analysis of 209 recorded gas dynamic phenomena at Xinjing Mine, the following outburst characteristics and patterns were summarized:

(1) Spatial distribution characteristics: All gas dynamic phenomena occurred at mining faces, with 115 instances (55%) at coal mining faces and 94 instances (45%) at heading faces, with no records from other areas.

(2) Type distribution characteristics: Ejections were predominant (193 instances, 92%), with outbursts (12 instances, 6%) and extrusions (4 instances, 2%) being relatively rare.

(3) Geological structure influence: 54% of gas dynamic phenomena were associated with geological structures, with 31% (66 instances) near faults, 14% (29 instances) in coal seam erosion zones, 6% (12 instances) affected by folds, and 3% (6 instances) influenced by composite structures.

(4) Outburst precursor characteristics: 76% of gas dynamic phenomena exhibited outburst precursors, with abnormal coal structure accounting for 64% (134 instances), coal cannon sounds for 53% (110 instances), abnormal coal seam thickness for 8% (16 instances), and abnormal drilling for 7% (15 instances), with some phenomena displaying multiple overlapping precursors.

(5) Coal structure influence: 88% of gas dynamic phenomena occurred at locations where the coal destruction type reached III-IV, indicating that soft coal distribution is a crucial condition for outburst occurrence.

(6) Prediction indicator characteristics: The drill cuttings gas desorption index K1 demonstrated good outburst prediction effectiveness, with 84% of dynamic phenomena exceeding a K1 value of 0.5 $mL/g \cdot min^{1/2}$, while the drill cuttings volume index S showed insignificant changes, with 95% of measurements falling between 2.5 and 3 kg/m.

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(7) Outburst intensity characteristics: Small to medium-sized outbursts were predominant, with only one medium-sized outburst (202.99 tons of coal and rock ejected, with 15,862 m^3 of gas emitted) and the rest being small outbursts or extrusions.

3. Intelligent Early Warning Indicator System and Model for Coal and Gas Outbursts

3.1. Construction of the Early Warning Indicator System

Based on the characteristics and patterns of coal and gas outbursts at Xinjing Mine, and considering the mine's mining conditions, development methods, and actual prevention and control technologies, an early warning indicator system covering three dimensions—production system, region, and working face—was established, adhering to the principles of purposefulness, scientificity, systemicity, proactivity, and feasibility. The system is presented in Table 1.

Table 1. Early warning indicator system for coal and gas outbursts at Xinjing mine

Indicator type	Primary indicators	Secondary indicators
Production system risk early warning indicators	Mining and excavation deployment	Coal seam mining sequence, arrangement of mining and excavation spatial positions, succession of gas extraction, mining, and excavation
	Gas extraction system	Gas extraction system capacity, whether gas extraction meets standards
	Ventilation system	Fan capacity, degree of ventilation difficulty, whether zonal ventilation is implemented, whether dedicated return airways are set up, whether series ventilation exists
Regional risk early warning indicators	Gas geology	Whether in geological structure-affected area (zone)
	Mining and excavation stress	Whether in stress concentration zone, stress concentration factor
	Regional measure deficiencies	Whether in gas extraction blank zone, whether within measure control range, residual gas content (pressure) in coal seam
	Type of mining and excavation engineering	Whether it is upward tunneling, whether it is uncovering coal seam at cross-cut
Working face risk early warning indicators	Daily prediction	K1 value, change in K1 value
	Coal seam occurrence	Changes in coal seam thickness, changes in coal seam dip angle
	Coal mass structure	Thickness of soft layer, degree of damage
	Gas emission	Gas index A, desorption index B
	Mine pressure monitoring	Support working resistance, rib spalling depth
	Outburst precursors	Blowout holes / drill bit jamming / drill bit sucking, coal gun sounds
	Local measure deficiencies	Whether there are measure blank zones, measure control range, measure advance distance, measure implementation time

3.2. Multi-source Information Fusion Early Warning Model

A multi-source information fusion early warning model based on association rules and evidence theory is employed to achieve comprehensive decision-making and early warning across multiple indicators. The model construction steps are as follows:

(1) Data Preprocessing: Collect and organize relevant data on coal and gas outbursts, including gas parameters, geological structures, prediction indicators, and mining progress. Normalize the data to eliminate the impact of differing units of measurement.

(2) Association Rule Mining: Calculate the support (Si) and confidence (Ci) of each early warning indicator using association algorithms. Screen key early warning indicators and establish associations between indicators and outburst risks.

(3) Evidence Theory Modeling: Based on the confidence calculated through association rules, establish basic confidence calculation rules and construct an identification framework U = {Red Early Warning, Orange Early Warning, Green Early Warning}.

(4) Evidence Synthesis and Decision-Making: For newly acquired indicator values, construct a basic confidence distribution table and apply evidence synthesis algorithms for fusion analysis to determine the early warning level.

(5) Model Self-Evolution and Optimization: Based on feedback on the accuracy of early warning results, recalculate indicator support and confidence every 15 days and update the confidence distribution rules to achieve model self-correction and self-evolution.

4. Construction of the Intelligent Early Warning System for Coal and Gas Outbursts

4.1. Overall System Architecture Design

According to the intelligent early warning process for coal and gas outbursts, the overall system architecture is designed to consist of four core modules: monitoring and acquisition module, professional analysis module, outburst early warning module, and early warning database, as shown in Figure 1. The system adopts a closed-loop process of "monitoring and detection - information acquisition - professional analysis - early warning dissemination" to achieve online monitoring, intelligent identification, and real-time early warning of outburst risks.

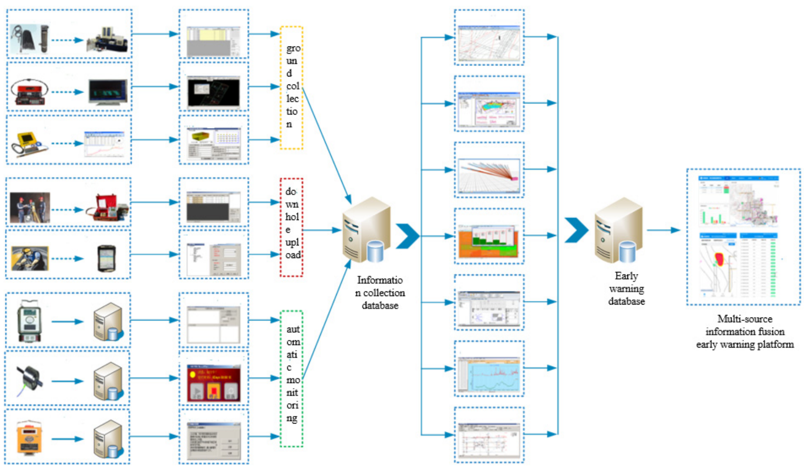

Figure 1. Framework of the intelligent early warning system for multi-source information on coal and gas outbursts at Xinjing mine

4.2. Implementation of Core Module Functions

(1) Monitoring and Acquisition Module

Relying on the coal mine underground ring network and surface office network, a multi-source information acquisition network architecture is constructed to enable automatic collection of various types of foundational safety information. 1)Gas Parameter Acquisition: Utilize the DGC coal seam gas content direct measurement device and data analysis software to achieve networked transmission of gas content measurement results. 2)Geological Anomaly Detection and Acquisition: Equip with geophysical exploration devices such as the YCS40 transient electromagnetic instrument and KJH-D ground-penetrating radar. Through the acquisition client program embedded in AutoCAD, automatically collect detection result maps and information on anomalous zones. 3)Borehole Trajectory Measurement and Acquisition: Use the ZKG borehole trajectory measurement device and data acquisition client program to export borehole trajectory data as text or Excel files and automatically upload them. 4)Outburst Parameter Acquisition: Employ the WTC-I outburst parameter instrument and utilize underground wireless base stations and the ring network to achieve automatic underground transmission of indicators such as K1 and S. 5)Gas/Mine Pressure/Drainage Monitoring and Acquisition: Develop dedicated data acquisition interface programs for the KJ90NB coal mine safety monitoring system, drainage monitoring system, and mine pressure monitoring system to achieve continuous real-time data collection.

(2) Professional Analysis Module

The professional analysis module primarily comprises seven professional analysis subsystems, providing foundational support for early warning analysis. 1)Geological Survey Management and Analysis Subsystem: Enable information management of geological exploration boreholes, shaft engineering, and geological structures, draw digital mine maps, and provide spatial foundational data. 2)Gas Geology Dynamic Analysis Subsystem: Based on GIS technology, achieve management of gas geology foundational data, analysis of gas geology patterns, and dynamic drawing of gas geology maps. 3)Drainage Borehole Management and Analysis Subsystem: Provide intelligent design of gas drainage boreholes, construction management, automatic drawing of completion diagrams, and intelligent identification of borehole blank zones. 4)Online Evaluation Subsystem for Drainage Compliance: Automatically analyze gas drainage patterns, assist in designing drainage borehole projects, and evaluate gas drainage compliance online. 5)Outburst Prevention Dynamic Management and Analysis Subsystem: Manage information on daily outburst prevention predictions and measures implementation, statistically analyze outburst prevention prediction indicators, and analyze deficiencies in outburst prevention measures. 6)Mine Pressure Monitoring and Analysis Subsystem: Manage mine pressure observation data, analyze mine pressure variation characteristics, and determine mine pressure anomalies online. 7)Gas Emission Dynamic Analysis Subsystem: Clean gas monitoring data, analyze gas emission characteristics, and determine gas emission anomalies online.

(3) Outburst Early Warning Module

1)Intelligent Early Warning Analysis Service: Adopt a Windows service mode for continuous background operation, collect foundational data in real-time, apply a multi-source information fusion model to calculate early warning indicators, and determine early warning levels. 2)Intelligent Early Warning Website: Provide functions such as querying the latest and historical early warning results, early warning level statistics, and early warning factor statistics, supporting query analysis and spatial analysis of early warning foundational data. 3)Intelligent Early Warning Mobile Terminal APP: Support Android and iOS platforms, enabling query and statistical analysis of early warning results and foundational information, facilitating on-site personnel to stay informed of early warning dynamics in real-time.

(4) Early Warning Database

Based on the principles of hierarchical autonomy and aggregated analysis, a four-tier database system is constructed: 1)Information Acquisition Database: Store foundational safety information collected from monitoring systems and detection equipment, containing over 40 information tables. 2)Professional Analysis Database: Comprise seven professional databases, each storing specialized data required for the operation of respective analysis subsystems. 3)Comprehensive Database: Store early warning foundational information obtained from the

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analysis of various professional subsystems, containing over 80 information tables. 4) Intelligent Early Warning Database: Store early warning foundational information, analysis results, and model parameters, containing over 20 information tables.

5. Field Application and Effectiveness Analysis of the System

5.1. Test Process

The intelligent early warning system for coal and gas outbursts at Xinjing Mine was completed in June 2018 and began its application demonstration in July, divided into three stages:

(1) Initialization Stage (January-June 2018): Historical outburst prevention information from typical outburst prevention working faces in the No. 3 coal seam and data on 209 instances of gas dynamic phenomena were collected and organized. After digitization and storage, automatic analysis was conducted to calculate the support and confidence levels of indicators, establish confidence distribution rules for early warning levels, and form a preliminary early warning model.

(2) Evolution and Improvement Stage (July-October 2018): Seven heading faces and one mining face were selected as subjects for observation. Real-time early warnings were issued and actual outburst risks were tracked. The early warning model was optimized and updated every 15 days, ultimately forming a stable and fixed early warning model.

(3) Early Warning Application Stage (November-December 15, 2018): The final early warning model was used to track and issue early warnings for outburst prevention working faces in the No. 3 coal seam, covering a cumulative length of 457.6 meters in headings and 128.5 meters in mining faces.

5.2. Self-adaptability Analysis of the Early Warning Model

During the initialization and evolution and improvement stages, continuous monitoring of the support, confidence, and critical values of early warning indicators revealed that as the model was continuously optimized, the support and confidence levels of early warning indicators gradually stabilized. After the optimization of preferred items and the fixation of confidence distribution rules, no significant changes occurred. Indicators such as the K1 value, gas indicator A, rib spalling depth, and coal burst sounds maintained high support and confidence levels, becoming core early warning indicators. Indicators such as soft layer thickness and degree of destruction maintained low support but high confidence levels, serving as important auxiliary early warning indicators. Some indicators with low support and confidence levels were automatically screened out, demonstrating the model's self-learning and self-evolution capabilities.

5.3. Accuracy Analysis of Early Warnings

(1) Results from the Evolution and Improvement Stage

The results of the evolutionary advancement phase are as follows: 1)Heading Faces: The overall accuracy of early warnings gradually increased from 81.78% in early July to 91.56% in late October. The rate of missed outburst risks appeared only once in the initial stage (20%) and stabilized at 0% thereafter. The false alarm rate for non-outburst risks decreased from 18.18% to 8.44%. 2)Mining Faces: The overall accuracy of early warnings gradually increased from 82.22% to over 91%. There were no missed outburst risks throughout the process (miss rate of 0%), and the false alarm rate for non-outburst risks decreased from 19.05% to below 9%.

(2) Results from the Early Warning Application Stage

Among the seven working faces tracked and observed, except for the 3109 return airway, which had an early warning accuracy of 90.82%, the remaining six working faces all exceeded 91%, with the highest accuracy of 92.14% in the 3216 cutting. The overall early warning accuracy for the mine was 91.52%. The miss rate for outburst risks was 0% across all working faces, with no missed alarms. The false alarm rate for non-outburst risks was 9.01% for the 3216 air distribution roadway and below 9% for the others, with an overall mine rate of 8.54%, meeting the requirements for coal mine safety early warnings.

5.4. Typical Case Analysis

On July 4, during the morning shift in the east main roadway of the No. 8 coal seam in the Lunan No.1 District, the K1 value reached 1.49 mL/g·min$^{1}/^{2}$, indicating a daily prediction exceedance. The system issued an orange trend early warning on the midnight shift of July 2, upgraded the status early warning to "threat" during the morning shift on the same day, and further upgraded the trend early warning to red on the midnight shift of July 3. It issued an outburst risk early warning two days in advance, providing sufficient time for the implementation of outburst prevention measures. After measures were taken at the working face on July 4, the early warning results returned to normal on July 5. The gas emission indicators showed an initial increase followed by a decrease, consistent with the "zoning and banding" distribution pattern of outburst risks, verifying the reliability of the early warning results.

6. Conclusion

(1) Through statistical analysis of 209 instances of gas dynamic phenomena at Xinjing Mine, seven major characteristics and patterns of coal and gas outbursts, including spatial distribution, type distribution, and geological structure impacts, were revealed, providing data support for the construction of the early warning indicator system.

(2) An early warning indicator system covering three dimensions—production system, region, and working face—was constructed, and a multi-source information fusion early warning model based on association rules and evidence theory was developed, featuring self-learning and self-evolution capabilities.

(3) By integrating four major modules—monitoring and acquisition, professional analysis, early warning dissemination, and database—an intelligent early warning system for coal and gas outbursts was established, enabling automatic collection of multi-source information, professional data analysis, intelligent identification of outburst risks, and real-time dissemination of early warning results.

(4) Field application results showed that the system achieved an overall early warning accuracy of 91.52%, with a miss rate for outburst risks of 0% and a false alarm rate for non-outburst risks of 8.54%. The early warning effectiveness was satisfactory, providing effective technical support for safe production in outburst-prone mines.

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