Creativity and Innovation
2025, VOL. 9, NO. 5, 396-400
DOI: 10.47297/wspciWSP2516-252779.20250905

# Research on Risk Situation Assessment and Early Warning Model of Major Disasters in Coal Mine Based on Complex System Theory

Ziming Xu[1]*, Junwei Shi[1], Jianguo Xu[2], Gang Liu[1], Yongzhen Wang[1]

[1]Shandong Technology and Business University, Yantai, Shandong, 264005, China

[2]Linyi Mining Group Heze Coal and Electricity Co., Ltd. Pengzhuang Coal Mine, Linyi, Shandong, 276018, China

**ABSTRACT**

This study addresses the monitoring and early warning challenges of coupled disaster risks in coal mine complex systems through theoretical research and practical applications of risk situation assessment and early warning models. By analyzing the formation mechanisms and coupling characteristics of major disasters such as gas outbursts, coal spontaneous combustion, water hazards, and rock burst, combined with dynamic risk assessment theory, we developed a multi-task learning and multi-factor adaptive integration framework for early warning models. The research introduced advanced technologies including quantum computing fractal algorithms, an improved particle swarm optimization support vector machine (IPSO-SVM), and a BO-LightGBM dual-warning model, significantly enhancing the accuracy and timeliness of risk identification. Engineering applications demonstrate that the new model reduces disaster recognition time from 48 hours to 6 hours while decreasing false alarm rates by 62%, providing an effective technical pathway for achieving the "transparent perception and intelligent prediction" safety governance model in coal mines.

**KEYWORDS**

Coal mine disaster; Risk situation assessment; Early warning model; Multi-task learning; Intelligent early warning

## 1 Introduction

The coal mine production system is a complex mega-system formed by the interaction of multiple elements including geological structures, mining activities, ventilation networks, and environmental conditions. It features intricate internal connections, significant dynamic changes, and high nonlinearity with inherent uncertainty. In recent years, as coal resource extraction progresses deeper into underground layers, mining conditions have become increasingly complex, with engineering and geological challenges such as high ground pressure, elevated temperatures, and severe gas accumulation becoming more prominent. Major disasters like gas outbursts, spontaneous coal combustion, water hazards, and rock burst not only occur more frequently but also exhibit characteristics of multi-disaster coupling, chain-like evolution, and intensified suddenness. These disasters often trigger each other, forming compound disaster patterns that dramatically increase prevention and control difficulties. Traditional single-factor, single-disaster monitoring methods, failing to adequately consider the interactive effects and spatiotemporal linkage mechanisms within the system, struggle to comprehensively reflect the dynamic evolution of disaster risks. This has gradually rendered them inadequate for modern intelligent coal mine construction and safety requirements. Therefore, scholars and research institutions worldwide have reached a consensus: A comprehensive approach must be adopted. By comprehensively sensing and deeply integrating multi-source information from geology, mining operations, ventilation systems, and stress analysis, combined with advanced technologies like artificial intelligence, big data analytics, and simulation modeling, we can establish an intelligent early-warning and comprehensive risk assessment system for coal mine disasters. This system enables early identification, dynamic evaluation, and proactive alerts of disaster risks, significantly enhancing intelligent disaster prevention capabilities and emergency response efficiency in coal mining operations.

## 2 Major coal mine disaster types and coupling characteristics

### 2.1 Main disaster types and their characteristics

Major coal mine disasters primarily include gas hazards (outbursts, explosions), spontaneous coal combustion, water inrush, rock burst, and roof disasters. These hazards exhibit distinct formation mechanisms and characteristics: Gas outbursts and explosions mainly occur when mining activities disrupt the original stress balance of coal seams, causing adsorbed gas to rapidly release. Explosive risk zones form when methane concentration reaches 5%-16% with oxygen content exceeding 12%. Spontaneous coal combustion arises from oxidation reactions in fractured coal seams within mined-out areas when oxygen concentration surpasses 14%. The oxidation rate increases exponentially with every 10°C temperature rise, releasing heat equivalent to 3500 kJ/kg. Water inrush is predominantly influenced by geological structures like faults and fissure zones, with coal mine water surges typically associated with heavy rainfall or excavation-induced breaches of waterproof layers. Rock burst occurs when mining activities cause stress redistribution, accumulating

*** Corresponding Author:** Zingmi Xu, 2329774297@qq.com

elastic strain energy in rock strata that suddenly releases energy, creating dynamic phenomena.

### 2.2 Disaster coupling mechanism and composite disaster pattern

In deep mining environments, multiple hazards often trigger each other and evolve through chain reactions, forming complex disaster patterns. These processes demonstrate remarkable dynamism and positive feedback characteristics. Typical chain reactions include: The massive heat released by coal spontaneous combustion rapidly elevates the temperature of gas-mixed gases accumulated in mined-out areas or fractures, reaching explosive thresholds; Meanwhile, the combustion or explosion of gas further heats coal bodies, accelerating oxidation reactions and creating a positive cycle under thermal-force-chemical coupling effects. Additionally, stress redistribution in surrounding rock caused by mining activities may induce impact ground pressure while damaging water-sealing coal pillars or activating dormant structures. This leads to the invasion of confined water along fractures, resulting in spatiotemporal superposition and coupled escalation of disasters. Such cascading expansion mechanisms of multi-hazard chains significantly increase the complexity of disaster prediction and prevention.

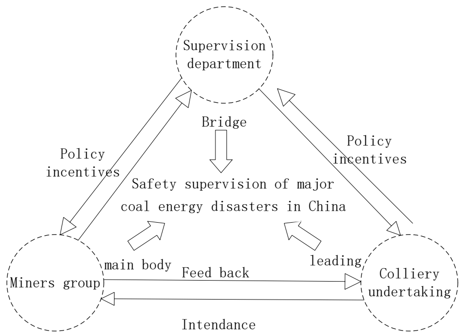


Figure 1 Safety supervision of major coal energy disasters in China

## 3 Risk situation assessment theory and technical basis

### 3.1 Dynamic risk assessment theoretical framework

The risk assessment of coal mine disasters is a dynamic process encompassing multi-dimensional factors including hazard-causing elements, vulnerability of disaster-bearing entities, and disaster prevention capabilities. Its theoretical framework consists of three key layers: multi-source information perception layer, risk analysis and evaluation layer, and decision support application layer. The multi-source information perception layer relies on a coordinated monitoring network deployed both above ground and underground to obtain real-time dynamic data from geological structures, mining activities, and environmental parameters. A typical example is the integrated "surface-underground" microseismic monitoring system established at Yuxi Coal Mine in Shanxi Province, which achieves millisecond-level high-precision response to rock mass stress changes and microseismic activities. Building upon this foundation, the risk analysis and evaluation layer utilizes big data fusion and artificial intelligence algorithms to deeply mine and intelligently identify multi-source heterogeneous data. A prime example is the intelligent inversion framework based on convolutional neural networks (CNN), which efficiently processes geological exploration data, improving the prediction accuracy of geological stress fields by approximately 23% compared to traditional methods while significantly enhancing the ability to identify pre-disaster precursors. Ultimately, the decision support application layer generates tiered early warnings and emergency response strategies based on dynamic assessments.

### 3.2 Key advances in risk assessment technology

With the rapid advancement of information technology, significant progress has been made in coal mine disaster risk assessment technologies, particularly in multi-source sensing, intelligent analysis, and early warning decision-making. In multi-parameter fusion identification, a high-precision distributed optical fiber temperature measurement system (with accuracy up to ±0.5° C) combined with gas chromatography technology (with detection limits as low as 0.001%) has enabled dynamic reconstruction of three-dimensional temperature-gas concentration fields in mined-out areas, providing quantitative evidence for risk assessment—— For instance, when the $CO:C_2H_4$ concentration ratio exceeds 200, it indicates that coal spontaneous combustion has entered the accelerated oxidation phase; while when $CH_4$ concentration is within the 5%-16% range with oxygen content above 12%, it suggests the formation of high-risk zones for gas explosions. Regarding dynamic evolution modeling, addressing the practical challenge of ground stress field inversion in near-fault zones, researchers proposed integrating numerical simulation with deep learning. By constructing high-precision three-dimensional geological structure models and introducing transfer learning mechanisms, this approach effectively overcomes model training difficulties under conditions of scarce field samples, thereby enhancing the reliability of geological dynamic system simulations. The model achieved an $R^2$ of 0.9129 in regression predictions and a classification accuracy exceeding 90%, demonstrating superior engineering applicability and reliable early warning performance.

## 4 Construction and optimization method of early-warning model

### 4.1 Integrated framework for multi-task learning

To address the complexity and interconnectivity challenges in coal mine disaster coupling early warning systems, this study proposes an integrated multi-task adaptive learning framework. By leveraging shared representation learning and task-specific parameter optimization mechanisms, the framework enables parallel evaluation and coordinated early warnings for multiple hazards including gas, fire, water hazards, and rock burst. The core architecture comprises three key components: 1) A common feature extraction network utilizes deep neural networks to perform hierarchical feature mining on multi-source monitoring data (e.g., microseismic signals, gas concentrations, stress fields), effectively capturing inherent correlations and coupled evolution patterns among different hazards; 2) Task-specific sub-networks develop specialized modules tailored to the disaster formation mechanisms of various hazards, maintaining precise modeling capabilities for unique physical processes and precursor patterns; 3) An adaptive fusion mechanism dynamically integrates multi-hazard warning outputs through attentional weight allocation strategies, achieving accurate quantitative assessment of coupled risk. Experimental results demonstrate that this multi-task learning framework significantly enhances model generalization performance under small-sample conditions through parameter sharing and end-to-end joint optimization, improving training efficiency by over 40% compared to traditional single-task models. Particularly in scenarios with scarce yet destructive rare hazards, the framework exhibits exceptional reliability and practical value in early warning applications.

### 4.2 Intelligent warning model innovation

This study focuses on innovating three intelligent early-warning models to enhance the accuracy and timeliness of coal mine disaster monitoring. First, the quantum computing fractal early-warning model emits multi-band chaotic pulse waves into coal-rock masses, capturing waveform responses that combine chaotic pulse characteristics with natural vibration components. Fractal dimension and Hurst index are used to quantitatively characterize fracture development in rock layers. The model further incorporates quantum annealing and hybrid quantum-classical annealing algorithms for efficient iterative solutions, significantly improving its capability to handle high-dimensional nonlinear coupling problems, particularly enabling precise detection of precursor features in micro-fracture networks within highly fractal geological environments. Second, the IPSO-SVM gas outburst prediction model employs grey relational analysis to quantify correlations between 10 primary influencing factors and outburst intensity. An enhanced particle swarm optimization (IPSO) algorithm dynamically optimizes inertia weights and learning parameters to improve global optimization capabilities.

### 4.3 Model optimization and verification strategy

To ensure the reliability and engineering applicability of the constructed early warning model, this study systematically adopted a multi-level optimization and validation strategy. First, a multi-stage verification mechanism was implemented. Model training was conducted using fivefold cross-validation with an early stopping strategy, optimizing hyperparameters for both regression and classification tasks. The Gaussian process prior and Expectation-Enhancement (EI) algorithm were employed to efficiently search for parameters, while LightGBM's histogram algorithm and leaf growth strategy effectively processed multi-source heterogeneous monitoring data, enhancing model robustness and generalization capabilities. Second, a dynamic threshold adjustment strategy was implemented. Risk warning indicators were iteratively optimized based on actual mine production feedback. For instance, in the Yuxi Coal Mine microseismic monitoring system, six moderate-risk and one low-risk alerts were adjusted to no-risk levels according to field conditions, significantly reducing false alarm rates and improving warning accuracy. Finally, a closed-loop feedback mechanism was established.

## 5 Challenges and future trends

### 5.1 Current technical bottlenecks

Although significant progress has been made in coal mine disaster early warning technology in recent years, several key technical bottlenecks remain in practical applications. First, the capture rate of composite disaster precursor information is generally insufficient. Current technologies demonstrate limited comprehensive perception capabilities for multi-disaster coupled signals, particularly under complex geological conditions where existing systems achieve only 43.6% capture rate of composite precursors, making it difficult to systematically identify interactive evolution characteristics between disasters like gas and spontaneous coal combustion. Second, the integration efficiency of multi-source heterogeneous data remains low. Data from different monitoring systems—such as microseismic, gas, and stress sensors—differ significantly in format, precision, and spatiotemporal reference, lacking unified coordination and integration mechanisms that hinder deep fusion and joint analysis of multidimensional information. Additionally, early

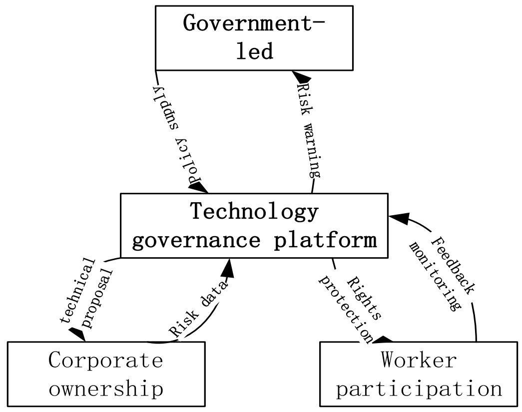


Figure 2 Quadripartite Governance Community architecture

warning models exhibit weak generalization capabilities. Most current models are built on specific mining areas or single disaster types, over-relying on static historical data while lacking modeling capacity for geological dynamics and mining process adaptability. This results in markedly reduced warning performance across different mining regions and scenarios. These issues severely limit the widespread adoption and practical effectiveness of coal mine composite disaster early warning systems.

### 5.2 Technological innovation direction

The future innovation and development of coal mine disaster early warning technology will primarily focus on the following directions: First, introducing federated learning technology to establish cross-mining data collaboration mechanisms. This approach ensures data privacy and security across mining areas while enabling distributed joint training and knowledge sharing of multi-source heterogeneous monitoring data, thereby significantly enhancing the generalization capabilities of early warning models under varying geological and mining conditions. Second, dedicated efforts will be made to develop Explainable Artificial Intelligence (XAI) models that provide intuitive decision-making bases and risk traceability pathways, strengthening engineers 'understanding and trust in model outputs to improve the system's acceptability and practical effectiveness. Finally, breakthroughs will be prioritized in "geophysical-chemical-thermodynamic" multi-field coupled early warning theory. By systematically integrating multi-process interactions such as stress fields, gas seepage, energy release, and chemical reactions during geological disaster evolution, we aim to construct more comprehensive and dynamic mathematical models for disaster evolution. This will provide solid theoretical support for achieving more precise and proactive warnings of complex coal mine disasters.

### 5.3 Technology integration and system integration

The future of coal mine disaster early warning technology will evolve through deep integration of multiple technologies and systematic innovation, aiming to establish a comprehensive, intelligent risk prevention system. Specifically, two key initiatives stand out: First, the "MineGuard AI" intelligent agent for comprehensive risk management, jointly developed by Taiyuan University of Technology and partners, integrates multi-source heterogeneous monitoring data to build dynamic knowledge graphs. This breakthrough overcomes traditional isolated and delayed safety management models, enabling intelligent decision-making from disaster detection and smart diagnosis to precise early warnings. Second, the "Microseismic Localization + Geological CT" platform combines microseismic monitoring with geological CT scanning to achieve transparent, three-dimensional real-time monitoring of rock structures and stress fields in mining areas. This significantly enhances early identification of potential hazards, providing critical data support for both workplace safety and post-disaster rescue operations.

## 6 Conclusions and outlook

This study systematically analyzes theoretical methods and technical practices for assessing risk scenarios and early warning systems in complex coal mine systems, yielding the following conclusions: First, the coupled effects of multiple coal mine disasters necessitate systematic thinking and integrated approaches for risk prevention. Independent early warning models for single disasters struggle to adapt to complex environments under deep mining conditions, requiring the establishment of a multi-disaster coupling early warning framework. Second, AI-driven and big data-powered intelligent warning models have significantly improved the accuracy and timeliness of coal mine disaster alerts. Third, engineering applications have validated the feasibility and effectiveness of these new warning technologies. The implementation of microseismic monitoring networks, composite disaster warning systems, and meteorological disaster prevention mechanisms has transformed coal mine safety governance from "reactive response" to "proactive early warning," substantially enhancing operational safety. Future research should focus on four key areas: 1) Developing cross-mining federated learning platforms to address small-sample training challenges; 2) Deepening multi-field coupling mechanism studies to reveal inherent patterns in disaster chain evolution; 3) Promoting digital twin technology applications to enable real-world-virtual-world bidirectional mapping and feedback; 4) Establishing integrated warning-response-control systems to form a complete closed-loop from risk identification to disaster mitigation. Through continuous technological innovation and system optimization, the coal mine disaster risk early warning will gradually achieve the goal of "transparent perception, intelligent prediction, accurate early warning and automatic control", and finally build an intrinsically safe coal mine production system.

## Funding

The work was funded by the Natural Science Foundation of Shandong Province of China(NO: ZR2024MG039):Research on Risk Sensing and Early Warning Decision-Making of Major Coal Mine Disasters Based on Multimodal Big Data.National Undergraduate Training Program for Innovation and Entrepreneurship 2024 (NO: 202411688008); Shandong Province Science and Technology Small and Medium-sized Enterprises Innovation Capacity Promotion Project(NO: 2024TSGC0400)

## About the Author

Ziming Xu,Undergraduate, Safety Engineering.

## References

[1] Yanhui Li,Youwei Zhang,Yulong Hu. Discussion on the Application of Intelligent Coal Mine Systems under Complex Geological Conditions [J]. Shaanxi Coal, 2022,41(01):113-117.

[2] Guorui Su. Research on Key Hidden Hazards Identification and Safety Risk Prediction in Coal Mine Accidents [D]. Liaoning Technical University, 2022.

[3] Guofa Wang, Huaiwei Ren, Guorui Zhao, et al. Intelligent Coal Mine Data Model and Coupling Technology System for Complex Giant Systems [J]. Journal of Coal Science, 2022,47(01):61-74.

[4] Junwei Shi. Risk Evolution Assessment and Prevention of Coal Mine Rockburst Accidents [D]. Anhui University of Science and Technology, 2021.

[5] Lizhen Tian. Current Status and Prospects of Intelligent Mining Technology Research in Coal Mines [J]. Contemporary Chemical Industry Research, 2020, (23):13-14.

[6] Jing Hao. Research on Intelligent Control Methods for Ventilation Systems in Large Complex Coal Mines [J]. Mechanical Management Development, 2020,35(10):170-171.

[7] Jian Lin, Jizu Li. Research on Factors Influencing Miner Self-Discipline from the Perspective of Complex Adaptive Systems [J]. China Safety Production Science and Technology, 2019,15(12):163-168.

[8] Anyi Wang, Jingjing Ma,Chaoyang Liu. Implementation of a Complex Electromagnetic Environment Assessment System in Coal Mines [J]. Coal Mine Safety, 2018,49(11):106-109.

[9] Xudong Zhu, Zhongliang Lu, Zhili Wang, Etc. Research on Resistance Reduction in Complex Ventilation Network Mines —— Taking Jiaozhai Coal Mine as an Example [J]. Journal of Henan Polytechnic University (Natural Science Edition), 2018,37(06):37-43.

[10] Liang Wang. Event-Driven Detection and Early Warning of Underground Coal Mine Safety Incidents [J]. Mining Automation, 2016, 42(08): 33-37.

[11] Xiangjiao Sun. Fracture Study of Coal Mine Ventilation Safety Systems [D]. China University of Mining and Technology, 2015.

[12] Xianguo Li. Complexity Mechanism and Control of Major Gas Accidents in Chinese Coal Mines [D]. China University of Mining and Technology, 2010.

[13] Jinxian Zhao. Application of Fracture Theory in Coal Mine Production System Risk Assessment [D]. Harbin Engineering University, 2010.

[14] Youli Yao. Chaotic Control of Human-Machine-Environment Coal Mine Safety Systems Based on Bifurcation Theory [J]. China Journal of Safety Science, 2010,20(03):97-101.

[15] Gang He. System Analysis and Dynamic Simulation of Coal Mine Safety Influencers [D]. Anhui University of Science and Technology, 2009.

[16] Hongmei Wu. Fracture Theory in Complex Systems and Its Application in Coal Mine Accident Systems [D]. Harbin Engineering University, 2009.