Theory and Practice of Science and Technology
2025, VOL. 6, NO. 9, 221-225
DOI: 10.47297/taposatWSP2633-456942.20250609

Research on Major Disaster Risk Situation Prevention and Control System Based on Stamp / Stpa Control and Feedback Model in Coal Mine

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ABSTRACT

Coal mine safety production serves as a crucial safeguard for China's energy strategy. However, major disasters such as gas, water, fire, roof collapse, and dust remain serious threats to its sustainable development. Traditional single-disaster prevention systems suffer from issues like "information silos," insufficient accuracy of early warning models, and lack of multi-disaster coordination capabilities. To address these challenges, this study aims to develop an integrated and intelligent risk management system for major coal mine disasters. The research first analyzes the risk characteristics and coupling mechanisms of primary coal mine hazards, establishing a four-layer architecture comprising perception layer, transmission layer, storage-analysis layer, and application layer. By integrating multi-source heterogeneous data from safety monitoring, personnel positioning, and geological information through fusion technology, the system employs machine learning algorithms and multi-field coupling models to build an intelligent early warning framework for disaster risks. This enables dynamic risk assessment and proactive alerts. Furthermore, digital twin and visualization technologies are utilized to visually present mine safety conditions and simulate disaster progression. Practical applications demonstrate that this system significantly improves early warning accuracy and timeliness, facilitates coordinated multi-system operations and emergency command, establishes a closed-loop risk management system, and provides crucial theoretical support and technical solutions for coal mining enterprises to build intelligent safety assurance systems.

KEYWORDS

Major disasters; Risk situation awareness; Early warning model; Multi-source data fusion; Stamp / Stpa Model

1 Introduction

As a critical safeguard for China's energy security, coal mine safety management continues to face threats from various major disasters. Analysis of recent accident statistics reveals that hazards including gas explosions, coal and gas outbursts, water inrush accidents, roof collapses, mine fires, and dust explosions remain frequent occurrences. These incidents have caused severe casualties and property losses, significantly hindering the high-quality development of the coal industry. Current coal mine disaster monitoring and early warning systems exhibit notable shortcomings: independent operation of subsystems, inconsistent data standards, and poor information interoperability, creating severe "information silos." Moreover, existing early-warning models predominantly rely on single-factor approaches with limited accuracy and high false-alarm rates [1]. They lack comprehensive analytical capabilities for multi-hazard coupling mechanisms, making it difficult to achieve early risk identification and coordinated prevention measures.

With the rapid advancement of next-generation information technologies such as the Internet of Things (IoT), big data, and artificial intelligence, it has become feasible to establish comprehensive systems for monitoring and managing major coal mine disaster risks. These integrated systems combine multi-source heterogeneous monitoring data from geological conditions, environmental factors, equipment operations, and personnel activities to develop dynamic risk assessment models. By enabling coordinated perception, intelligent analysis, and proactive early warnings for multiple hazards including gas accumulation, water hazards, roof collapses, and fires, they significantly enhance overall disaster prevention capabilities and emergency response efficiency in coal mining operations.

2 Theoretical analysis of risk of major coal mine disasters

2.1 Main types and characteristics of coal mine disasters

Coal mining operations face diverse and complex hazards, including gas disasters (e. g., explosions and outbursts), water-related incidents (such as flooding and water surges), roof failures (like collapses and roof falls), fires (both spontaneous combustion and electrical sparks), and dust hazards (which may trigger explosions and are primary causes of occupational pneumoconiosis in miners). These disasters typically exhibit sudden onset, chain reactions, and interconnected effects. The occurrence of a primary disaster can easily trigger secondary events, creating complex cascading mechanisms that significantly increase operational uncertainty and complicate risk management.

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The coupled effects of multiple disaster types, characterized by mutual triggering and amplification, have broken the operational boundaries of traditional single-disaster monitoring and prevention models. This reveals critical shortcomings in current single-disaster management systems when addressing complex mine environments and cascading hazard scenarios. Therefore, developing an integrated risk management system that combines multi-source information, identifies disaster linkages, simulates chain reactions, and enables coordinated control has become an essential direction for enhancing coal mines' comprehensive disaster resilience [2].

2.2 Risk situation awareness and assessment theory

The prevention and control of major coal mine disaster risks is grounded in systematic theory and full lifecycle management principles. By implementing comprehensive monitoring across four dimensions— "human-machine-environment-management" —the system achieves closed-loop management from risk identification, assessment, early warning to containment. This integrated framework covers the entire lifecycle from mine planning and design through production, construction, and post-operation maintenance, aiming to enable early risk detection and proactive intervention before disasters occur.

Risk situation awareness forms the foundation for real-time monitoring and intelligent decision-making in mining systems. The system integrates and processes diverse data types: static data includes geological structures, coal seam conditions, roadway layouts with support systems, equipment models and installation locations; dynamic data covers environmental parameters, equipment operational status , as well as personnel positioning and behavioral data [3]. Through IoT sensors and smart terminals in the perception layer, the system achieves real-time collection and high-frequency transmission of massive, heterogeneous data. By leveraging data fusion techniques to eliminate information conflicts and supplement missing data, it ultimately constructs a comprehensive, accurate, and up-to-date panoramic view of mine safety conditions.

In risk assessment, the system adopts a strategy combining multi-criteria evaluation methods with machine learning algorithms. First, based on disaster mechanisms and historical accident data, it constructs a multi-dimensional risk warning indicator system covering hazard source status, environmental factors causing disasters, and disaster prevention facility effectiveness. Subsequently, methods such as Analytic Hierarchy Process (AHP) and Entropy Weighting Method are employed to determine indicator weights, followed by preliminary risk quantification through fuzzy comprehensive evaluation [4]. Furthermore, machine learning algorithms are introduced. By analyzing large-scale historical monitoring data, these algorithms uncover potential risk evolution patterns and multi-factor coupling relationships, establishing more precise dynamic risk assessment and prediction models. Such models not only evaluate individual disaster risks but also analyze chain reactions and coupling effects among multiple disaster factors, enabling comprehensive simulation and trend forecasting of complex disaster scenarios. This significantly enhances the accuracy, reliability, and timeliness of risk warnings.

3 System overall architecture design

3.1 Design objectives and principles

The design of the coal mine major disaster risk situation prevention and control system aims to achieve four core objectives: comprehensive perception, intelligent analysis, precise early warning, and collaborative management. The system construction strictly follows the following key principles: First, the system adopts the principle of uniformity, relying on unified data standards, collection specifications, storage architecture, analytical processes, and visual presentation to achieve deep integration, sharing, and intelligent mining of multi-source heterogeneous data, providing a consistent and reliable data foundation for disaster warnings. Second, the system emphasizes compatibility and scalability [5], seamlessly integrating with current monitoring systems while reserving standardized interfaces and modular architecture to support future functional expansion and technological iteration. Finally, the system centers on intelligence, deeply integrating big data analysis, artificial intelligence algorithms, and self-learning mechanisms to achieve autonomous risk assessment, adaptive optimization of early warning models, and continuous improvement of decision-making capabilities, thereby establishing a truly intelligent perception and cognitive system for coal mine disaster prevention and control.

3.2 System hierarchy

The coal mine major disaster risk prevention system adopts a layered and decoupled four-tier architecture design, covering the perception-control layer, transmission layer, storage-analysis layer, and application layer to achieve closed-loop management from data collection to intelligent services [6]. The transmission layer utilizes hybrid communication networks including industrial Ethernet, 5G, and LoRa to ensure high-reliability, low-latency data transmission and real-time command delivery, maintaining data integrity in complex underground environments. The storage-analysis layer is built on a big data platform to form a unified mining data center. This layer integrates multi-source heterogeneous data through storage, governance, and deep analysis, while incorporating data computing engines, machine learning algorithm libraries, and model training platforms to support continuous development and optimization of risk warning models. Through web interfaces and mobile terminals, it delivers flexible and intuitive integrated service interfaces for diverse users, ultimately achieving proactive perception, intelligent analysis, and collaborative control of major coal mine disasters.

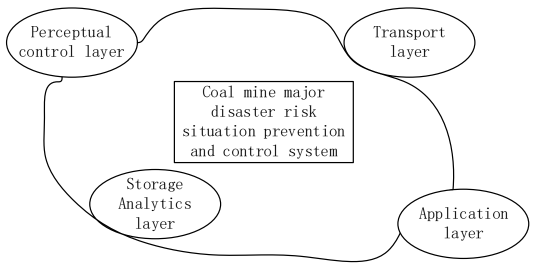

Figure 1 System architecture composition

3.3 System functional modules

The Coal Mine Major Disaster Risk Management System integrates core functional modules to establish a comprehensive, multi-tiered disaster prevention framework. The Monitoring Data Integration Module centralizes access, cleanses, and stores multi-source heterogeneous data, effectively resolving data silos while supporting real-time processing and historical management, thereby providing high-quality data foundations for intelligent risk analysis. The Multi-disaster Early Warning Module utilizes integrated multi-factor prediction models to conduct coordinated analysis and dynamic alerts for water hazards, fires, gas incidents, roof collapses, and dust exposures. This module features warning indicator management, model configuration, and alert rule customization, significantly enhancing the system's capability to identify and respond to compound disasters. The Safety Status Evaluation and Visualization Module combines 2D/3D GIS with digital twin technology to create high-precision digital representations of mine environments. It enables multidimensional visualization of safety risks through an integrated platform supporting disaster evolution simulations and spatiotemporal risk distribution mapping. This closed-loop management system from early warning to response feedback comprehensively elevates coal mines' collaborative disaster response capabilities and emergency efficiency.

4 Key technologies are implemented

4.1 Multi-source isomerism data fusion technology

The comprehensive risk prevention system for major coal mine disasters requires integrated data from multiple subsystems including safety monitoring, personnel positioning, video surveillance, hazard management, and 3D geological modeling. Key implementation strategies include: 1) Data extraction and cleansing through ETL tools, followed by handling missing values and outliers while implementing standardization to ensure consistent quality; 2) Integrating multi-source data through spatiotemporal tagging and entity identification to establish intrinsic connections between "human-machine-environment-management" elements, forming a comprehensive data set that holistically characterizes mine safety conditions; 3) Implementing big data platform technologies at the storage and management level, creating a distributed computing infrastructure that combines data lakes, data warehouses, and real-time streaming engines. This architecture enables efficient access and real-time analysis of massive multi-source datasets, providing robust data support for risk early-warning systems and decision-making processes.

4.2 Risk warning model and algorithm

The system incorporates specialized indicators such as "inter-day water inflow" (for flood hazards) and "support resistance", tailored to specific disaster types. In determining indicator weights, it combines subjective weighting methods like the Analytic Hierarchy Process (AHP) with objective approaches including entropy weighting, balancing expert expertise with data characteristics to ensure scientifically sound weight allocation. For model construction, the system integrates multiple early-warning analysis models: multivariate linear regression models establish predictive relationships between factors like gas explosion risk and gas concentration, temperature, and wind speed; coupled multi-field models reveal cascading and coupling mechanisms among multiple disasters [7]. These models are often fused through ensemble learning to enhance prediction accuracy and robustness. Additionally, the system demonstrates self-learning and adaptive capabilities, dynamically adjusting parameters and structures based on new data to continuously adapt to evolving mining conditions, ultimately achieving more reliable and intelligent risk situation awareness and early warnings.

4.3 Digital twin and visualization technology

Digital twin technology achieves real-time data interaction and dynamic linkage between physical mines and digital models through constructing high-fidelity virtual representations. This digital twin integrates multidimensional data including geological structures, real-time equipment status, and environmental parameters, enabling precise physical entity description, system modeling, trend prediction, and operational optimization within virtual environments. Key features include: 1) Three-dimensional panoramic views of underground and surface areas, utilizing high-precision geological and roadway models combined with real-time monitoring data to achieve transparent management and dynamic visualization across the entire mine space; 2) Risk heat maps that visually represent risk levels through color gradients, clearly illustrating spatiotemporal distribution patterns and evolution trends; 3) Disaster simulation systems that dynamically simulate the entire process of hazard occurrence and development using physics engines and mathematical models, scientifically assessing impact ranges and evolutionary trends to provide visual references for disaster warnings and emergency decision-making.

4.4 Emergency decision making and multi-system linkage technology

When the system detects critical risks or receives early warning alerts, the emergency decision-making module automatically activates and swiftly enters emergency response mode. CBR identifies historical disaster scenarios to provide successful case studies for similar situations. RBR performs logical evaluations and process activation based on predefined safety protocols and emergency procedures. MBR utilizes disaster evolution simulations and consequence prediction models to dynamically simulate catastrophe progression while assessing the effectiveness of different measures. During plan generation, the system considers multidimensional factors such as disaster type, risk level, impact scope, real-time personnel distribution, equipment status, and escape route availability [8]. Through multi-objective optimization algorithms, it produces optimal response strategies that balance time efficiency, personnel safety, and control effectiveness.

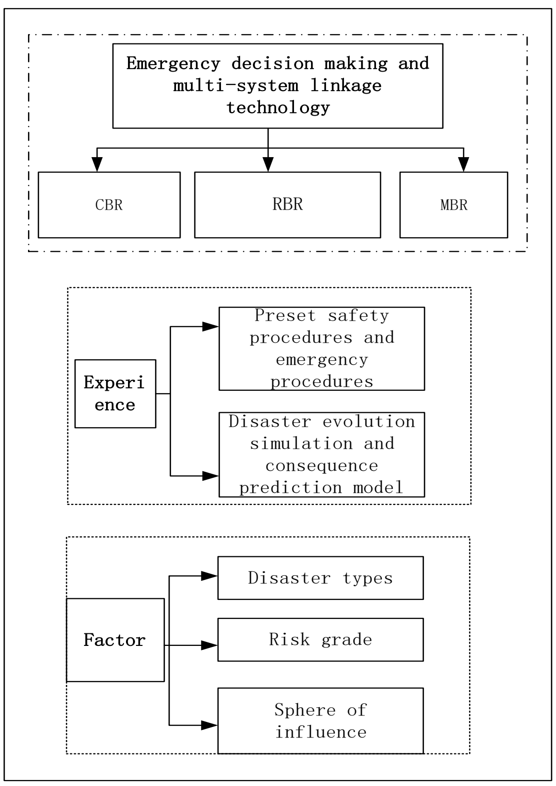

Figure 2 Method path

The multi-system integrated control technology employs a unified intelligent management platform to deeply integrate and coordinate multiple subsystems including underground environmental monitoring, ventilation, drainage, power supply, communication, positioning, and broadcasting [9]. For instance, when detecting excessive gas concentration in a specific area and confirming risks, the system not only triggers audible/visual alarms and sends warnings to both surface and underground operations but also automatically executes emergency controls: immediately cutting off power supply in affected zones to prevent spark-induced explosions; simultaneously activating personnel positioning systems to quickly plan and issue optimal evacuation routes; issuing directional evacuation orders through emergency broadcast systems and personnel tracking cards to guide affected workers to safety; while adjusting ventilation systems and activating dust suppression/dilution devices to contain hazards. This process achieves intelligent coordination among multiple systems, significantly enhancing coal mines' automated emergency response capabilities and risk resistance levels [10].

5 Conclusions and outlook

This study systematically investigates the construction methodology of a risk prevention system for major coal mine disasters, yielding the following conclusions: The system effectively addresses issues such as "information silos" and delayed early warning in traditional single-disaster prevention systems by integrating multi-source monitoring data, constructing intelligent early-warning models, and enabling multi-system collaboration. Its four-layer architecture—comprising perception layer, transmission layer, storage-analysis layer, and application layer—enables closed-loop management throughout the entire process from data collection, transmission, analysis to application, significantly enhancing system integrity and reliability. The organic integration of key technologies including multi-source heterogeneous data fusion, intelligent early-warning models, digital twin visualization, and emergency decision-making coordination ensures efficient system operation and precise early-warning capabilities. Practical applications demonstrate that this system substantially improves disaster warning accuracy and timeliness, reduces accident occurrences, enhances emergency response efficiency, and demonstrates significant safety, economic, and social benefits. Looking ahead, while significant progress has been made, further research is needed to deepen understanding of multi-field coupling disaster mechanisms to strengthen theoretical foundations for early-warning models; develop high-precision, highly-reliable sensing technologies and equipment; improve self-learning and adaptive capabilities of early-warning models to better adapt to complex mine environments; and continuously advance digital twin technology in mining to achieve more accurate disaster simulation and emergency scenario modeling. With the continuous integration of emerging technologies including artificial intelligence, 5G, and blockchain, the coal mine major disaster risk prevention system will evolve toward smarter, more efficient, and more reliable capabilities. This will ultimately establish an intelligent prevention framework featuring self-awareness, autonomous analysis, smart decision-making, and dynamic adjustment mechanisms, providing comprehensive and reliable safeguards for coal mine safety production.

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)

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