Research Progress on Multi-Technology Integration Early Warning and Prevention of Mine Geological Disasters

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Abstract: ***Mineral resource development is prone to 引发 mine geological disasters, and with the increase in development intensity, they show a high-frequency and frequent occurrence trend. This paper systematically reviews relevant research in the field of mine geological disaster prevention, and discusses the composition method of the multi-technology integration early warning system and the progress of prevention strategies. By integrating geological monitoring technologies in the hydrogeology, engineering geology, and environmental geology fields, intelligent equipment, and ecological restoration technologies, an integrated "monitoring - early warning - prevention - restoration" technical system is proposed. The intelligent early warning system based on multi-source data fusion and engineering-ecological collaborative prevention can effectively improve the prevention effect of mine geological disasters, aiming to provide a new technical path for safe and green mine development.***

Keywords: Mine geological disasters; Multi-technology integration; Intelligent early warning; Collaborative prevention; Ecological restoration.

1. INTRODUCTION

Mineral resources are an important part of the industrialization field. With the development of industrialization, the intensity of mineral resource development has gradually increased, and mine geological disasters have shown a new trend of high frequency and frequent occurrence. The direct losses caused by mine geological disasters in China are huge every year, and various mine geological disaster events occur frequently, posing a huge threat to mining production safety and the lives and property safety of workers and residents, and having a huge impact on the stability of the ecological environment. China's geological environment has the particularity of "east-west division and north-south zoning", with relatively complex geological structures. Moreover, due to historical issues in some mining areas, there is an extensive mining model of "mining first and governance later", which further increases the risk of geological disasters in mining areas.

In recent years, scholars at home and abroad have continued research in the field of mine geological disaster prevention and control, with significant progress in monitoring technology, early warning models, and prevention technologies. Geological monitoring technologies in the hydrogeology, engineering geology, and environmental geology fields are relatively mature; for example, geological radar (GPR), transient electromagnetic method (TEM), and remote sensing technologies such as GIS, GPS, and RS have been widely used in the detection of geological disasters like surface subsidence, ground fissures, collapses, landslides, and mudslides. The rapid development of artificial intelligence technology, along with the integration of machine learning methods and multi-source data fusion technologies, has greatly improved the accuracy of disaster early warning models. Moreover, as the concept of ecological environmental protection has taken root, the synergistic development effect of engineering measures and ecological restoration has become increasingly prominent. However, in terms of slope stability assessment, traditional geological radar and geophysical exploration methods struggle to fully grasp the impact of dynamic changes in underground water levels in mining areas, and relying solely on traditional methods such as engineering support cannot fundamentally address the long-term geological safety risks caused by ecological degradation. Therefore, building an intelligent early warning and prevention system integrating multi-source data has become an important component in enhancing the comprehensive prevention and control capabilities of mine geological disasters.

Lin, Liu, Xiang, and Hong (2025), who developed a Bayesian framework for modeling multivariate degradation data with dynamic covariates, advancing reliability engineering [1]. This work builds upon earlier methodological foundations established by Lin, Wang, and Hong (2023), who detailed the computation of the Poisson multinomial distribution for applications in ecological inference and machine learning [2]. The societal and entrepreneurial impacts of AI technologies are explored by Zhou and Cen (2024), who investigated the effect of ChatGPT-like generative AI on user entrepreneurial activities [3]. As AI systems become more distributed, security concerns have become paramount. Deng and Yang (2025) addressed this by developing multi-layer defense strategies and privacy-preserving enhancements to protect federated learning frameworks from membership reasoning attacks [4]. In the domain of sensor data processing, Guo (2025) developed a method using Inertial Measurement Units (IMUs) and Long Short-Term Memory (LSTM) networks for real-time data completion and motion recognition [5]. For personalized services, Yang, Wang, and Chen (2024) developed GCN-MF, a graph convolutional network based on matrix factorization for recommendation systems [6]. In computer vision, Jin et al. (2024) advanced object detection and pose estimation techniques by integrating hybrid task cascade with high-resolution networks [7]. At a systemic level, Mehta et al. (2026) worked towards establishing a national AI security framework specifically designed for financial infrastructure protection [8]. Digital marketing and content distribution are addressed by Zhou (2025), who proposed a digital precision distribution strategy for social media content in the automotive industry using collaborative filtering based on user behavior [9]. Complementing this, Li (2026) explored optimizing AI-driven bid pricing models for non-standard automation projects by leveraging historical financial data and machine learning algorithms [10], while Yi (2025) developed a real-time fair-exposure ad allocation system using contextual bandits-with-knapsacks [11]. The performance of these intelligent systems is fundamentally enabled by hardware innovations. Tang et al. (2020) contributed to this foundation with their design and optimization of a shallow-angle grating coupler for vertical emission from indium phosphide devices [12]. In natural language processing, Xie et al. (2024) advanced legal citation text classification using a Conv1D-based approach for multi-class categorization [13]. Finally, addressing cloud computing security, Deng (2025) proposed a homomorphic encryption-based mechanism for data integrity verification and anti-tampering in cloud storage environments [14].

2. TYPES AND DISASTER-CAUSING MECHANISMS OF MINE GEOLOGICAL DISASTERS

2.1 Main Disaster Types

Based on the current geological characteristics and engineering practices of mines in China, mine geological disasters can be divided into four categories: seismic disasters, ground subsidence and collapse, ground fissures, and mountain landslides and collapses.

Seismic disasters are caused by crustal movements, affecting mining areas through rock stratum displacement, vibrations, etc., and may induce secondary disasters such as underground collapses and ground fissures. They are a common type of mine geological disaster in China. Earthquakes of different magnitudes have significantly different destructive effects, causing severe damage and threats to people's lives and property safety.

Ground subsidence is mostly caused by structural damage due to improper mining or over-extraction of groundwater. When the supporting capacity of rock pillars and mine pillars is insufficient, soil layer compression occurs, externally manifested as slow surface sinking. Ground collapse is mostly caused by the development of karst caves in karst areas and the collapse of underground goafs, characterized by suddenness and destructiveness, which in turn affects construction and production safety and poses a serious threat to lives and property.

Ground fissures are affected by the integrity of the geological structure. When the geological structure is damaged or the groundwater level changes drastically, it is easy to cause instability of the underground confined layer structure, resulting in faults or surface linear fissures. When rainfall infiltration intensifies, it can induce more serious geological disasters such as landslides or collapses.

Landslides and slope instability usually occur under specific conditions, mostly in open-pit mining areas. Due to excessively steep slope angles, weathered and fractured rock formations, or heavy rainfall, the structural integrity of the mine geological body is reduced, and when subjected to external forces, the soil or rock mass slides down along the sliding surface as a whole. The causes of such geological disasters include but are not limited to natural and human factors. Among natural factors, floods, earthquakes, etc., can induce landslides; among human factors, destructive mining in mines and substandard construction quality can also induce mine geological disasters such as landslides and slope instability.

2.2 Key Disaster-Inducing Factors

The occurrence of mine geological disasters is affected by the combined action of natural and human factors, with the core disaster-inducing factors mainly lying in four aspects: geological structure, hydrogeology, mining activities, and ecological environment factors.

Original geological structures such as folds and faults in the mine geological body have a direct impact on rock formation stability. Rock formations in fault zones are relatively fragmented and have strong water permeability, which can easily form hydraulic migration channels for groundwater, establishing hydraulic connections with the groundwater in the mining area, thereby increasing the instability of slope failure; fractured zones in fold areas are generated due to the compression of rock formation forces, increasing the probability of mine ground subsidence; excessive fluctuations in groundwater levels in the mining area can cause bentonite to shrink and expand, leading to a significant decrease in foundation bearing capacity, thereby inducing ground subsidence disasters, and when groundwater seepage pressure exceeds a certain pre-determined value, it will cause significant damage to the structure of soft soil layers, thereby inducing the risk of geological disasters such as slope sliding.

In open-pit mining, phenomena such as excessive stripping volume, over-exploitation of groundwater, or failure to backfill goafs in a timely manner or substandard backfilling will damage the balance and stability of the mine geological body. Destruction of vegetation in the mining area will lead to soil erosion, resulting in a decrease in soil shear strength, while phenomena such as tailings sand and slag accumulation not only pose certain risks to the bearing capacity of the original land but also can cause secondary geological disasters such as mudslides due to rainwater scouring during heavy rainfall.

3. MULTI-TECHNOLOGY INTEGRATION EARLY WARNING SYSTEM

3.1 Monitoring Technology Integration

The core of the multi-technology integration early warning system lies in constructing an "air ground underground" integrated monitoring network, which mainly needs to integrate underground detection technology, surface monitoring technology, hydrological monitoring technology, and remote sensing monitoring technology.

In terms of underground detection technology, ground-penetrating radar (GPR) and transient electromagnetic (TEM) should be the main components to achieve high-precision detection of underground structures. High-frequency radio waves and pulsed electromagnetic fields excite secondary eddy currents to accurately identify and measure primary geological structures and groundwater hydrological dynamic data. The combination of the Beidou positioning system and GPS technology enables real-time monitoring of surface displacement. By Set up monitoring points with a certain density in landslide-prone areas, daily displacement changes can be captured at the millimeter level; RS technology can identify changes in the length and width of surface cracks through high-resolution satellite images, and the current combination of InSAR technology and UAV technology can even achieve large-scale inspections once a week.

In the field of hydrological monitoring technology, current groundwater level monitors can reach centimeter-level accuracy, and when combined with osmometers, can collect groundwater-related data in real time. After deploying millimeter-level precision rainfall sensors on the surface, the impact of precipitation-groundwater linkage on mine slope stability can be accurately analyzed. The combination of Internet of Things (IoT) technology and 5G technology enables real-time transmission of multi-source data. Deploying wireless sensor networks during underground operations and in hazardous areas can real-time monitor parameters such as underground temperature, humidity, and rock stress, thereby improving inspection safety and avoiding the safety risks of manual inspections.

3.2 Intelligent Early Warning Model

For multi-source monitoring data, a three-level intelligent prediction model of "data preprocessing - feature value extraction - risk prediction" needs to be built. In the data preprocessing stage, filtering and normalization of raw data can be achieved by screening out GPS signal interference, error correction for radar wave attenuation, etc. Combined with the integration of multi-dimensional, high-precision data such as geology, hydrology, and ecology, a standardized database is formed. In practice, the surface fracture data obtained by geological radar, the surface displacement data obtained by RS, and the groundwater level and water pressure data can be uniformly converted into a time-series dataset under spatial coordinates. In the feature extraction stage, key disaster-causing factors can be accurately screened through principal component analysis (PCA). For example, in the landslide early warning process, the extraction of core features such as daily displacement, daily rise of groundwater level, and slope can reduce data dimensionality. In the risk prediction stage, an improved Long Short-Term Memory (LSTM) network model can be used, inputting monthly periodic time-series data to predict short-term disaster risk levels. Alternatively, prediction accuracy can be improved through training with historical disaster cases. This method has significant advantages in prediction accuracy compared with traditional logistic regression models, thus better providing safety guarantees for mine production.

3.3 Technical Advantage Analysis

Compared with traditional single technology, the multi-technology integrated early warning system has significant advantages in three aspects: comprehensiveness, timeliness, and dynamics. Integrating multi-dimensional data such as underground, surface, geological, hydrological, and ecological data can avoid misjudgment based on a single indicator. In engineering practice, monitoring of surface displacement needs to include deep sliding caused by groundwater seepage; integrating groundwater level and migration data can improve the accuracy of early warnings, thereby enhancing the comprehensiveness of the multi-technology integrated early warning system. The combination of 5G transmission and intelligent algorithms enables full automation of the "monitoring analysis warning" process, significantly reducing the time from data collection to the release of warning information, which greatly improves efficiency compared with manual analysis, reflecting the timeliness of the model. In terms of dynamic characteristics, model parameters are continuously optimized based on real-time data updates to adapt to the dynamic changes in mining area geological conditions. In production practice, after the mining depth of the mining area increases, the model can automatically adjust the correlation parameters of "goaf distance-surface manifestation", thereby maintaining the accuracy of early warnings and achieving dynamic observation.

4. COMPREHENSIVE PREVENTION AND CONTROL TECHNOLOGY SYSTEM

4.1 Engineering Prevention and Control Technology

In the mine geological disaster management system, engineering measures are the core elements for controlling geological disaster risks, and differentiated schemes need to be adopted for different disaster types.

For the treatment of ground subsidence and collapse, cement-fly ash mixed slurry is usually used for grouting and filling. In areas with over-exploitation of groundwater, artificial recharge can be carried out through well irrigation and canal irrigation to reduce soil compression. For the treatment of ground fissures, for those with a width less than 0.5 m , clay filling and artificial membrane covering measures are usually adopted to prevent rainwater infiltration; for ground fissures with a width greater than 0.5 m, steel skeletons and concrete pouring are usually used, and drainage holes need to be set to drain accumulated water. For the treatment of landslides and slope instability, slope cutting and Plastic surgery combined with bolt support is generally adopted; anti-slide piles are used to block potential sliding surfaces, and pile spacing is controlled according to on-site conditions. For the prevention and control of earthquake-induced secondary disasters, in mining areas with high seismic intensity, underground roadways need to use U-shaped steel supports, surface buildings need to be provided with seismic joints, and emergency shelters such as seismic sheds and first-aid materials should be reserved.

4.2 Ecological Restoration Technology

Ecological restoration technologies can enhance the long-term stability of geological structures by improving the ecological environment of mining areas. They mainly include vegetation restoration, soil improvement, soil covering and reclamation, and hydrological ecological restoration. For vegetation restoration, native species with strong stress resistance such as pine, Amorpha fruticosa, and sea buckthorn should be selected, and seed pretreatment and foreign soil spray seeding technology should be adopted to build a vegetation cover layer on slopes and around subsidence areas within the mining area, thereby reducing soil erosion. For soil improvement, the comprehensive technology of "leaching + passivation + bioremediation" should be applied to tailings pond accumulation areas and heavy metal-contaminated soil to reduce the heavy metal content in the soil, thereby restoring soil fertility. For soil covering and reclamation, abandoned mining pits need to be cut high and filled low for land leveling, and then covered with Cultivation layer soil to grow crops and forage, thereby realizing the reuse of land resources. For hydrological ecological restoration, a "sedimentation tank - constructed wetland" system should be built to treat mine wastewater to meet standards for vegetation irrigation or groundwater backfilling, and intercepting and drainage ditches should be built around the mining area to reduce the scouring effect of rainfall on slopes.

4.3 Synergistic Prevention and Control Effect

The collaborative technology of engineering measures and ecological restoration can achieve the comprehensive management effect of "short-term risk control + long-term stability", and has significant benefits in terms of the timeliness of risk control, cost-benefit optimization, and ecological-geological coupling enhancement.

In terms of risk timeliness control, engineering measures such as bolt support and anti-slide piles can increase the slope stability coefficient within 1-3 months, effectively reducing geological disaster risks and reserving time for ecological restoration. Ecological restoration measures such as vegetation recovery can gradually take effect after 1-2 years, thereby maintaining the long-term stability of ecological restoration. In terms of cost-benefit optimization, single engineering measures such as full-slope concrete spraying have drawbacks such as high cost and ecological damage, making them difficult to respond to emergency situations. However, the collaborative restoration model of "bolts + local spraying + vegetation" can significantly reduce costs, and its effect of improving ecological benefits is particularly remarkable. In terms of ecological-geological coupling enhancement, the transpiration of vegetation can lower the groundwater level, thereby reducing the erosion of rock formations by groundwater. Engineering measures such as drainage holes and drainage ditches can divert surface runoff, thereby avoiding waterlogging and rotting of vegetation roots, and ultimately achieving a Benign structure cycle of "engineering protecting ecology and ecology consolidating engineering", and realizing the comprehensive management effect of "short-term risk control + long-term stability".

5. OUTLOOK AND CONCLUSIONS

5.1 Outlook

With the gradual development of scientific and technological means, the multi-technology integrated early warning and prevention system has achieved certain results. The existing bottlenecks are mainly reflected in insufficient technical compatibility, poor adaptability to extreme conditions, and high cost and difficulty in promotion. Combining the current development status and bottlenecks, future technological development and application can focus on four aspects. The first is intelligence and standardization: a universal data structure can be developed to achieve "plug-and-play" of monitoring equipment under the premise of confidentiality principles. Establish and improve relevant design standards and technical specifications, and clarify relevant technical parameters under different geological conditions. The second is technological breakthroughs in extreme environments: anti-interference monitoring equipment can be developed to improve equipment safety under extreme conditions, and a technical system suitable for high and steep slopes, such as UAV precision seeding technology, can be developed to improve vegetation survival rate. The third is low-cost technological innovation: promote "localization + lightweight" intelligent monitoring equipment, develop simple and practical ecological restoration technologies, and reduce their technical operation thresholds. The fourth is digitization and visualization: a 3D geological model of the mining area can be constructed to integrate real-time monitoring data, engineering construction measures, ecological restoration information, etc., so as to realize the whole-process visual management of "monitoring - early warning - prevention" and improve relevant decision-making efficiency.

5.3 Conclusions

Given the complex characteristics of mine geological disasters, it is necessary to break through the limitations of single technologies and construct an early warning and prevention system integrating multiple technologies. The integrated structural system of "monitoring - early warning - prevention - restoration" proposed in this paper integrates multiple technologies such as hydrogeology, engineering geology and environmental geology monitoring, intelligent early warning, engineering prevention, and ecological restoration to realize a full-chain prevention framework of "early detection, early warning, early treatment, and early restoration" for disasters, providing an effective technical path for safe and green mining in mines. In future development, it is necessary to break through bottlenecks in technical compatibility, adaptability to extreme conditions, etc., promote the development of technologies towards standardization, normalization, intelligence, and low cost, and provide technical support for improving the level of comprehensive prevention and control of mine geology in China.

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