

Research on the Optimization of Dynamic Monitoring and Early Warning Systems for Open-Pit Slope Stability

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Abstract: The stability of open-pit mine slopes is affected by geological, hydrological, and mining factors. Current dynamic monitoring technologies include both traditional and emerging methods, yet the early warning systems still show deficiencies, particularly in indicator systems. To address these issues, optimization directions include: constructing a multi-dimensional collaborative monitoring network to achieve integrated three-dimensional monitoring; adopting an “edge computing+cloud analysis” approach for data processing and optimizing fusion algorithms; applying hybrid architectures to improve early warning models; and implementing a “microservice+containerization” system architecture to enhance the accuracy and reliability of slope monitoring and early warning.

Keywords: Open-pit mine slope stability; dynamic monitoring; early warning system optimization

1. Factors Influencing the Stability of Open-Pit Mine Slopes

1.1 Geological Factors

Geological factors are the fundamental determinants of open-pit slope stability, mainly including soil and rock properties, geological structures, and rock mass configurations. Rocks with different lithologies possess distinct physical and mechanical properties, which lead to varying impacts on slope stability: weak rock layers are prone to plastic deformation and failure, thereby

inducing slope instability; hard rock layers, although strong and generally stable, may develop fractures under geological structural forces, undermining the overall integrity of the slope^[1]. Faults, folds, and joints further reduce rock mass strength by destroying its continuity, while simultaneously creating pathways for groundwater infiltration, which exacerbates slope failure risks.

1.2 Hydrological Factors

Hydrological factors primarily affect slope stability through groundwater conditions. The distribution, flow,



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and dynamic changes of groundwater significantly influence the mechanical properties of rock and soil. Groundwater increases pore water pressure, reduces effective stress and shear strength, and its seepage may wash away fine particles, thereby weakening rock mass structures. Rainfall also saturates surface soils, increases self-weight, and intensifies groundwater effects, collectively elevating the risk of slope failure.

1.3 Mining Factors

Mining activities are critical anthropogenic factors influencing slope stability, mainly involving mining methods, depth, and rate. Different mining methods induce different levels of disturbance to slopes, which may lead to the development of fractures and loosening in rock masses. Although mechanical excavation is relatively moderate in impact, it still alters stress distribution within slopes. As mining depth increases, slope height and angle also rise, resulting in greater self-weight and stress on the slope, which in turn reduces its overall stability.

2. Current Status of Dynamic Monitoring Technologies for Open-Pit Mine Slope Stability

2.1 Traditional Monitoring Technologies

Traditional monitoring methods form the foundation of slope stability assessment.

(1) Surface deformation monitoring primarily relies on leveling, triangulation, and GPS measurements. Leveling and triangulation offer high precision but are inefficient, making them suitable for small-scale, high-accuracy monitoring. GPS monitoring enables large-scale dynamic observations with all-weather and automated advantages; however, it is more susceptible to satellite signals and environmental conditions, resulting in relatively lower accuracy ^[2].

(2) Deep displacement monitoring is used to evaluate internal rock mass deformation. Inclinerometers measure tilt angles at different depths within boreholes to calculate displacement, thereby reflecting internal deformation patterns. Borehole extensometers monitor elongation within rock masses to detect tensile deformation, making them suitable for deep-seated tensile displacement monitoring.

(3) Stress–strain monitoring employs stress meters and strain gauges to record stress and strain variations within rock masses, providing critical mechanical

parameters for stability analysis. However, monitoring point deployment and data interpretation are relatively complex.

2.2 Emerging Monitoring Technologies

Emerging technologies are driving slope monitoring toward greater efficiency and intelligence.

(1) Slope radar monitoring has become one of the mainstream approaches and is widely applied. Radar continuously scans slope surfaces to achieve long-distance, non-contact monitoring, with minimal influence from weather, lighting, or other environmental factors. It enables all-weather acquisition of real-time deformation data, covers large monitoring areas, and achieves high precision, allowing for the detection of subtle displacement changes. This provides crucial evidence for identifying potential slope instability, issuing warnings, and implementing preventive measures.

(2) Remote sensing technologies, including satellite, aerial, and ground-based remote sensing, enable rapid acquisition of large-scale slope information. Satellite remote sensing is suitable for macro-level monitoring, while aerial and ground-based approaches offer higher resolution and more detailed information.

(3) Internet of Things (IoT)-based monitoring deploys large numbers of sensor nodes to capture multiple slope parameters in real time. The collected data are transmitted wirelessly to centralized data centers for integrated management and analysis. This approach offers strong automation and real-time capabilities and represents one of the future development directions ^[3].

(4) Three-dimensional laser scanning rapidly acquires slope point-cloud data, which can be processed to obtain slope morphology and deformation information. It is characterized by high precision, speed, and non-contact operation, making it particularly suitable for monitoring in complex terrains.

3. Current Status of Early Warning Systems for Open-Pit Mine Slope Stability

3.1 Early Warning Indicator System

The early warning indicators for open-pit mine slope stability mainly cover four categories: deformation, stress, groundwater, and environmental factors. Deformation indicators (e.g., displacement magnitude and rate) directly reflect slope stability. Stress

indicators (e.g., rock mass stress magnitude and variation rate) reflect the internal mechanical state of the slope. Groundwater indicators (e.g., water level and pressure) significantly influence slope stability, while environmental indicators (e.g., rainfall and seismic intensity) are important triggers of instability^[4]. Current indicator systems have certain limitations, including incomplete selection of indicators, difficulty in data integration and analysis, and unreasonable weight determination, all of which reduce the accuracy and reliability of early warning results.

3.2 Early Warning Models

Early warning models for open-pit mine slope stability can be classified into three types: empirical, theoretical, and data-driven models. Empirical models rely on engineering experience; they are simple and practical but have a narrow scope of applicability. Theoretical models are based on geotechnical mechanics, such as the limit equilibrium method and finite element method. They can account for geological and mechanical characteristics but involve complex calculations and parameter dependencies. Data-driven models utilize monitoring data and offer strong nonlinear fitting capability but require a large number of training samples. Currently, these models face challenges in accuracy and generalization, making it difficult to adapt to complex slope conditions.

4. Optimization Directions for Dynamic Monitoring and Early Warning Systems of Open-Pit Mine Slope Stability

4.1 Collaborative Optimization of Monitoring Technology Systems

In dynamic monitoring of open-pit mine slope stability, collaborative optimization of monitoring technologies is a core factor for improving early warning effectiveness. This requires breaking the limitations of single technologies and promoting the deep integration of multi-dimensional monitoring methods, forming a mutually validating and complementary monitoring network. First, the coordination of different physical field monitoring technologies should be strengthened^[5]. Combining surface displacement monitoring with deep stress sensing allows for correlational analysis of deformation and stress. Incorporating hydrological data enables investigation of seepage effects and construction of multi-factor coupled models, avoiding

biases from single-indicator early warnings. To optimize this mechanism, a unified data standard should be established to eliminate information barriers from monitoring devices and ensure real-time parameter input from sensors to the analysis platform. Next, intelligent algorithms should be applied to fuse multi-source heterogeneous data, remove environmental noise, and extract key features of slope stability, improving data interpretation efficiency and accuracy. Attention should also be given to the coordination between static and dynamic monitoring. Static monitoring provides baseline data for long-term slope deformation, while dynamic monitoring captures short-term anomalous changes. Their combination enables comprehensive temporal coverage^[6]. A dynamic sampling mechanism can be established to automatically adjust monitoring frequency based on slope deformation rates (see **Table 1**). During stable periods, unnecessary monitoring resource consumption is reduced, while monitoring density is automatically increased when abnormal signs occur, achieving optimized resource allocation. Finally, monitoring technologies should be coordinated with on-site engineering practices. Monitoring data should be fed back to slope management plans in real time, and the reliability of monitoring models should be validated through actual mitigation outcomes. This feedback loop can be used to refine monitoring parameters and early warning thresholds^[7].

Table 1. Correspondence Between Slope Deformation Rates and Sampling Intervals

Slope Deformation Rate	Sampling Interval
< 0.5 mm/d	12 hours
0.5–2 mm/d	1 hour
> 2 mm/d	Real-time (minutes)

4.2 Optimization of Data Processing and Fusion Mechanisms

(1) Establish a two-tier “on-site processing+cloud analysis” architecture. Processing nodes equipped with simple intelligent modules are deployed at the monitoring site to quickly screen and filter out abnormal data caused by extreme weather events such as heavy rainfall or strong winds. Smoothed processing is then applied to reduce data fluctuations, retaining only the core parameters and compressing the data

volume to less than 30% of the original. On the cloud side, distributed storage is employed, with single nodes capable of 10 TB storage and receiving up to 100,000 data points per second. Leveraging time and location-based retrieval, historical data from the past three years can be accessed within milliseconds^[8].

(2) Optimize multi-source data fusion. Spatially, surface displacement monitoring data is correlated with subsurface sensor data to generate a 3D deformation distribution map with a resolution of 1 m × 1 m × 0.5 m. Temporally, a unified time standard is applied to data with different monitoring frequencies to avoid biases in deformation trend assessment. For heterogeneous data types, common features are extracted and calculation standards unified to eliminate errors caused by unit differences.

(3) Implement a “three-level verification” mechanism to ensure data quality. On-site nodes first check data completeness. The cloud platform then compares data from different devices within the same area for consistency. Finally, slope mechanics principles are

applied to verify the rationality of the data. Deviations exceeding 15% trigger re-examination, ensuring data reliability above 98%.

4.3 Dynamic Optimization of Early Warning Models and Thresholds

Early warning models and thresholds need to be constructed based on the mechanical properties of slope rock masses, environmental factors, and historical deformation patterns, forming an adaptive early warning mechanism. This ensures that warning signals accurately reflect slope conditions while avoiding excessive alerts that waste resources^[9]. At the model construction level, multi-source monitoring data should be integrated, and deep learning algorithms applied to uncover latent relationships between slope deformation and stability coefficients, allowing the model to adapt in real time to dynamic slope changes. The early warning logic should be customized for slopes in different areas according to site-specific geological conditions, avoiding biases caused by applying a uniform standard^[10] (see **Table 2**).

Table 2. Early Warning Levels, Trigger Conditions, and Corresponding Measures

Warning Level	Indicator Color	Trigger Conditions	Response Measures
Level I	Blue	Stability coefficient > 1.2	Record internally in the system only
Level II	Yellow	Stability coefficient 1.0–1.2 or displacement rate exceeds 50% of baseline	Push alert to management terminals
Level III	Orange	Stability coefficient 0.9–1.0 or accelerated deformation observed	Initiate on-site inspection
Level IV	Red	Stability coefficient < 0.9 or deformation rate increases more than 3-fold	Trigger emergency response mechanism

Through these optimizations, the accuracy of early warning can be improved to over 90%, providing reliable support for safety management of open-pit mine slopes.

4.4 Optimization of System Architecture and Functional Modules

The system architecture adopts a “microservices+containerization” deployment, breaking down functions such as data acquisition, processing, analysis, and early warning into independent modules. Dynamic resource allocation enables flexible scaling, with a single node capable of processing 5,000 tasks per second^[11]. The core server employs dual-machine backup, maintaining data synchronization delays within 10 milliseconds, preventing single-point failures, and achieving an

annual stable operation rate of 99.9%. Three core functional modules are added to the system. The 3D visualization module builds a digital model of the slope, supporting 1:1 real-scene reproduction and dynamic simulation of the deformation process, with real-time superimposed monitoring data heatmaps. The intelligent diagnosis module, which contains more than 200 typical landslide cases, can automatically match similar situations and provide corresponding treatment recommendations. The mobile terminal supports offline data queries and on-site photo uploads, combined with positioning to record inspection tracks, with real-time synchronization to the system. In terms of interfaces, standardized APIs are developed to ensure interconnection with mine production management

and safety monitoring platforms, enabling the linkage of slope monitoring data with production planning and equipment scheduling. The response time for data sharing is controlled within 2 seconds.

Conclusion

The optimization of dynamic monitoring and early warning systems for open-pit mine slope stability is a systematic engineering task, encompassing monitoring technologies, data processing, early warning models, and system architecture. By establishing a collaborative monitoring network, optimizing data processing and fusion mechanisms, improving early warning models and thresholds, and refining system architecture and functional modules, the system's monitoring accuracy and early warning capability can be substantially enhanced. Integrating aerial, satellite, and ground-based monitoring with intelligent algorithms enables a full-chain slope risk prevention and control framework. This approach facilitates the timely detection of slope instability, reduces accident risks, ensures mine safety, and shifts disaster management from reactive response to proactive prevention. With ongoing technological advances, the system is expected to become increasingly robust and capable of handling complex mining environments more effectively.

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