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Analysis of Slope Stability Management and Ecological Restoration Technologies in Open-Pit Mines

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Abstract: Open-pit mines, as the core carriers of mineral resource development, play a vital role in supporting socio-economic development. However, the risks associated with high and steep slope instability and ecological environmental damage are becoming increasingly prominent. Slope stability management is the prerequisite for ensuring safe mine production, while ecological restoration is the core path towards achieving sustainable mining development. With innovations in big data and artificial intelligence (AI) technologies, traditional management and restoration models are transitioning towards intelligent and precise transformation. By analyzing the core influencing factors of slope instability in open-pit mines, along with the practical challenges in management and restoration, this paper elaborates on a slope stability management technology system integrated with big data and AI, analyzes the implementation pathways for intelligent ecological restoration, and aims to provide theoretical support and practical references for constructing a coordinated "safety-ecology-long-term effectiveness" development model for open-pit mines.

1. Introduction

Open-pit mines have become the mainstream form of global mineral development due to advantages such as high mining efficiency, high resource recovery rates, and controllable working environments. However, mining requires surface stripping, forming high and steep slopes. Long-term exposure to complex environments makes mines prone to disasters like landslides, leading to production interruptions and threats to personnel safety. Simultaneously, it destroys vegetation, pollutes water and soil, causing ecological degradation in mining areas, which contradicts the concept of ecological civilization. Traditional management relies on experience, suffering from lagging monitoring and poor early warning; ecological restoration often faces challenges like poor effectiveness and high maintenance costs. Breakthroughs in big data and AI provide new pathways. By constructing a full-process technical system, they aim to achieve risk prevention and control and restoration optimization[1], promoting the transition of mines towards "proactive control" and "ecological reshaping," which is a current focus of research and practice.

2. Influencing Factors of Slope Instability in Open-Pit Mines and Challenges in Management and Restoration

2.1 Core Influencing Factors of Slope Instability

Slope instability in open-pit mines are caused by the combined effect of intrinsic geological properties and external triggering factors, where their superposition disrupts mechanical equilibrium. Among intrinsic factors, geological structures (faults, joints, etc.) disrupt rock mass integrity, forming weak sliding surfaces; lithological characteristics determine rock mass strength, with soft rocks prone to softening and spalling, while hard rocks offer greater stability; slope morphology (height, angle, bench width) affects stress distribution, and unreasonable parameters increase instability risk. External triggering factors act as "catalysts" for instability: rainfall infiltration increases slope weight and softens rock mass, with dynamic changes in groundwater exacerbating risks; improper mining techniques (unreasonable blasting parameters, incorrect excavation sequences) damage rock mass structure and stress balance; geological disasters (earthquakes, floods) increase the driving forces for sliding; surrounding human engineering activities (road construction, building construction) alter slope stress, further aggravating instability hazards[2].

2.2 Practical Challenges in Management and Restoration

The core challenge in slope management and restoration practice lie in the long-term balance between "safety stability" and "ecological sustainability." Although technologies for slope management and ecological restoration in open-pit mines continue to develop, multi-dimensional difficulties persist in practice. Firstly, technical synergy is insufficient: traditional engineering management (e.g., rigid support structures) often poorly connects with ecological restoration, easily becoming "concrete islands"; some ecological schemes neglect slope stability, blindly planting deep-rooted plants or disturbing rock masses, triggering safety risks. Secondly, environmental adaptability is weak: mining areas in China have significant climatic differences, with low vegetation survival rates in arid regions and slopes prone to frost damage in high-altitude cold regions; mine soils often have low fertility and prominent heavy metal contamination, making traditional improvement technologies difficult to adapt. Thirdly, data and long-term management control is lacking: slope instability may involve risks of "short-term stability, long-term gradual change," while traditional monitoring data is fragmented, lacking integration and analysis, making it difficult to reveal instability patterns and restoration constraints; most mines lack long-term maintenance mechanisms, causing management effects to easily diminish and struggle to maintain stable ecological functions. Fourthly, bottlenecks exist in the sustainability of ecological restoration: artificial substrates on rock slopes are prone to nutrient loss, leading to later vegetation degradation; blind introduction of alien species can easily disrupt ecological balance; soil improvement effects are difficult to sustain, easily forming a cycle of "restoration-degradation-re-restoration."

3. Slope Stability Management Technology Integrated with Big Data and Artificial Intelligence

3.1 Optimization of Engineering Management Technologies

Engineering management technologies are the fundamental guarantee for slope stability in open-pit mines. Their core objective is to adjust slope structure and strengthen slope force equilibrium through full-process technical control and management, fundamentally reducing instability risk. Support and reinforcement require precise selection based on instability type and geological conditions: anti-slide piles embedded into stable rock layers underground manage deep-seated landslides relying on embedded and frictional forces, offering strong load-bearing capacity and compatibility with ecological restoration; retaining walls are used for shallow protection, with reinforced soil retaining walls widely used in soft soil foundations due to their light weight and convenience; anchor rods (cables) combined with lattice beams support high and steep rock slopes[3], connecting shallow unstable rock masses with deep stable rock masses into a whole, restricting rock deformation, and preventing rock toppling or sliding.

Drainage and anti-seepage technologies are key means to eliminate water-induced instability risks. By constructing a synergistic "surface-underground" system, they quickly remove water from the slope surface, pores, and fractures, reducing pore water pressure and avoiding rock softening. Surface drainage intercept and diverts rainwater and runoff through catch drains, drainage ditches, and chutes. Catch drains are located outside the top of the slope to intercept surface runoff from above the slope crest, preventing water from flowing directly into the slope area; drainage ditches are arranged from top to bottom along benches and the slope toe, connecting with chutes to divert collected rainwater, preventing scouring and infiltration; when the slope angle of surface drainage ditches exceeds 15°, chutes need to be installed to prevent rainwater scouring from forming gullies. Underground drainage aims to lower the water table and eliminate seepage pressure through drainage holes, drainage galleries, and blind drains. Drainage holes, equipped with permeable pipes inside, drain pore water utilizing the water head difference; drainage galleries are suitable for draining deep groundwater, allowing large-scale drainage through excavated gallery facilities; blind drains, filled with permeable materials and placed inside the slope or at the toe, can collect and discharge groundwater from a larger area.

3.2 Construction of an Intelligent Monitoring and Early Warning System

The integration of big data and AI technologies promotes the transition of slope monitoring and early warning in open-pit mines from "passive response" to "active prediction," constructing a full-process, high-precision intelligent monitoring and early warning system.

Multi-source monitoring data fusion collection is the foundation of the system, requiring the integration of "space-sky-ground-underground" monitoring equipment. At the space level, InSAR technology is used, obtaining ground images via satellites or drones equipped with radar to achieve large-scale, all-weather, high-precision micro-deformation monitoring, capturing minor displacements. At the sky level, relying on drone aerial photography and high-resolution imaging, periodically capturing slope morphology and vegetation cover information assists in judging loose rock masses and cracks. At the ground level, GNSS monitoring stations obtain 3D coordinates of key points, enabling real-time dynamic displacement monitoring with millimeter-level accuracy[4]. At the underground level, inclinometers, stress gauges, and other equipment monitor rock mass displacement, stress, water level, etc., ultimately forming a three-dimensional monitoring network covering "surface-rock mass interior-surrounding environment."

Big data analysis and AI modeling are the core technical links for achieving intelligent and precise slope early warning. Firstly, multi-source monitoring data is preprocessed through big data techniques, performing data cleaning and constructing structured, standardized datasets. Then, through data correlation analysis, multi-source indicator fusion is completed, uncovering correlation patterns among monitoring indicators and identifying key influencing factors, providing key features for AI model input. Subsequently, the core AI modeling and risk warning phase employs machine learning classification models like Random Forest and Support Vector Machines to achieve real-time data stability classification. Finally, time series prediction models like LSTM and GRU, combined with probabilistic prediction models like Bayesian Neural Networks [5], output stability probabilities and predict deformation trends, providing risk quantification basis for early warning decisions, avoiding the limitations of single-threshold warnings.

Intelligent early warning and emergency linkage are the final implementation links of the intelligent slope monitoring and early warning system. Relying on AI models to establish dynamic warning thresholds, when a warning is triggered, executable emergency commands are automatically generated and pushed through multiple channels, linking with emergency systems to initiate graded responses, and reports on emergency linkage and continuous improvement are fed back to personnel, realizing a closed-loop management process of "warning-response-disposal-feedback." Meanwhile, AI technology can also optimize the layout of monitoring equipment. By using clustering algorithms to identify weak areas and potential instability points on the slope, it guides the precise placement of monitoring points, reducing monitoring costs while improving data effectiveness[6].

4. Ecological Restoration Technology Pathways Integrated with Big Data and Artificial Intelligence

4.1 Intelligent Vegetation Restoration Technology

Vegetation restoration is the core content of ecological restoration in open-pit mines. Its goal is to achieve soil and water conservation, soil improvement, biodiversity enhancement, and ecological landscape improvement by constructing stable plant communities. Big data and AI technologies can support the precise implementation of vegetation restoration. AI-assisted plant species selection is the primary step in vegetation restoration. Relying on a big data platform, it integrates multi-dimensional environmental data of the mine, including climate, soil, terrain data, and surrounding vegetation community structure data. Through AI algorithms such as decision trees and support vector machines, it matches environmental data with plant growth characteristics, simulates the growth adaptability of different plants, automatically matches the optimal combination scheme, and selects native plants that are suitable for the site and have strong stress resistance, replacing the traditional experience-dependent selection method. For example, drought-tolerant species like sea buckthorn and caragana are prioritized in arid and semi-arid mining areas for rapid ground cover; hyperaccumulator plants like Pteris vittate are preferred in heavy metal-contaminated mining areas for pollution remediation; in humid areas, a multi-level mix of trees, shrubs, and grasses is used to build stable plant communities.

Intelligent optimization of planting schemes is key to improving vegetation survival rates. Using digital twin technology to build a 3D model of the open-pit mine slope, importing parameters such as terrain, soil, and plant growth, simulates the effects of planting methods like hydroseeding, vegetation bags, cuttings, and direct seeding, matching the optimal planting scheme for the area, saving manpower and material resources while improving vegetation survival rates. Hydroseeding is suitable for high, steep, and relatively smooth slopes, where AI can optimize substrate ratios and spraying thickness; vegetation bags are suitable for uneven slopes, and AI analysis can match the optimal stacking density and binding methods, considering both ecology and safety; gentle slopes and platforms use cutting or direct seeding methods, with AI recommending the best planting time and density based on soil temperature and humidity, significantly improving planting effectiveness.

Automated construction technology is the core execution link of vegetation restoration. By integrating mechanical equipment, AI, positioning, and navigation technologies, it achieves "unmanned, precise, and efficient" operations, solving hazardous work risks while improving resource utilization. For high and steep slopes and complex terrain, automated drone seeding can be adopted, combined with GIS planning flight paths to achieve uniform seed distribution, forming a stable planting layer while avoiding the unevenness and safety risks of manual broadcasting. For the lower parts of mine slopes, substrate sprayers equipped with robotic arms can be used, remotely controlling the arm to adjust the spraying angle, ensuring comprehensive and dead-angle-free precise placement. For unstable slope sections, automated anchor cable and vegetation coordinated construction machinery is prioritized, achieving integrated "support-vegetation" construction, avoiding inconveniences caused by secondary operations.

Intelligent vegetation growth monitoring and maintenance are important supports for ensuring the stability of plant communities, primarily using devices for full-cycle dynamic management. Sensors, video surveillance, and regular drone inspections are deployed on the slope to collect real-time data on vegetation growth status and slope stability. Through drone aerial photography combined with hyperspectral imaging [7]. slope vegetation images are regularly obtained, and AI image recognition is used to automatically extract indicators such as coverage rate, chlorophyll content, and pests and diseases—yellowing leaves and low chlorophyll indicate water shortage or nutrient deficiency, spotted and curled leaves indicate pests and diseases. The big data platform and AI system integrate and process the monitoring data and analysis results, automatically generating the best maintenance plan: when water is scarce, it guides smart irrigation equipment for precise water replenishment; when nutrients are lacking, it pushes fertilization suggestions to equipment; for pests and diseases, it recommends biological or low-toxicity chemical control. The big data platform records the effectiveness of measures, and reinforcement learning algorithms continuously optimize strategies, forming a closed loop of "monitoring-analysis-maintenance-feedback," enhancing vegetation survival rates and community stability.

4.2 Soil Improvement and Landscape Reshaping Technology

Soil improvement is the foundation of vegetation restoration and needs to be tailored to mine soil characteristics and contamination types, with plans formulated using big data and AI. For soil fertility issues, successful improvement cases can be analyzed through big data, integrating data on the effects of organic and inorganic amendments to establish fertility prediction models, recommending the types and amounts of amendments based on initial soil data, such as adding lime to acidic soil to adjust pH, or adding compost to impoverished soil. For soils severely contaminated with heavy metals, AI is used to analyze the relationship between contaminating elements and soil properties, screening the best remediation technologies: using passivators to reduce heavy metal activity; inoculating functional microorganisms for bioremediation, where AI can predict their survival rate and reproductive capacity Rock slopes require the construction of artificial substrate layers[8], and big data analyzes the relationship between substrate material ratios and plant growth to optimize the formulation.

Landscape reshaping is an important means to enhance the ecological and aesthetic value of mines, requiring synergistic integration based on ensuring slope stability and ecological functions. Using GIS technology to overlay mine terrain, soil, vegetation, and surrounding landscape data, AI algorithms plan landscape functional zones: the slope face serves as the ecological protection area, planted with vegetation strong in soil and water conservation; platforms and abandoned pits serve as ecological landscape areas, constructing artificial lakes, ecological greenways, and viewing platforms combined with regional characteristics—the construction of artificial lakes can utilize big data to analyze hydrological conditions, greenways should follow topographic features to avoid interfering with slopes, viewing platforms can be set up in safe areas to exhibit restoration achievements[9]. Simultaneously, characteristic landforms such as rock outcrops and mining traces are preserved and ecologically transformed into industrial heritage landscapes, integrating "mining memory" with ecological functions, enhancing ecotourism value.

The combination of soil improvement and landscape reshaping technologies provides a suitable ecological environment for animals and plants, realizes the ecological function of slope stabilization and soil erosion prevention, improves landscape aesthetics, and achieves long-term economic development.

5. Collaborative Application of Management and Restoration Technologies and Long-term Management Control

5.1 Construction of Technical Synergy Mechanisms

The synergy between slope stability management and ecological restoration in open-pit mines needs to be based on the principles of "safety first, ecological adaptation, and technical integration," building a multi-technology collaborative application mechanism. In the connection between engineering management and ecological restoration, when implementing engineering measures such as support reinforcement and drainage, space for ecological restoration must be reserved—for example, designing vegetation planting troughs on the surfaces of anti-slide piles and retaining walls, filling soil substrate between lattice beams to provide conditions for subsequent vegetation restoration; before formulating ecological restoration plans, AI models must be used to assess the impact of vegetation planting on slope stability, avoiding damage to support structures by deep-rooted plants, prioritizing shallow-rooted plants with strong soil fixation capabilities, achieving dual guarantees of "engineering reinforcement + biological slope stabilization."

In terms of data synergy, an integrated mine intelligent platform is constructed, integrating slope stability monitoring data (deformation, stress, water level) and ecological restoration data (vegetation growth, soil improvement, hydrological environment). Big data technology analyzes the correlation between the two—when AI monitoring detects micro-deformation on the slope, it synchronously analyzes the vegetation growth status in the deformation area to determine if the micro-deformation is caused by root disturbance[10]. When soil improvement increases slope weight, it links with stability prediction models to assess the impact on slope stability, promptly adjusting the improvement plan to avoid new instability risks caused by soil loading.

In terms of technology selection synergy, for different mine geological and environmental conditions, an AI algorithm is used to build a technology adaptability assessment model—for example, in high and steep rock slope areas, the synergistic technology combination of "anchor rod (cable) lattice beam support + hydroseeding greening" is preferentially recommended, both ensuring slope stability through engineering measures and achieving ecological coverage through vegetation restoration; in soft soil slope areas, "reinforced soil retaining wall + vegetation bag greening" technology is adopted, considering both support effects and ecological restoration efficiency, avoiding the limitations of single technologies.

5.2 Construction of a Long-term Management and Control System

A dynamic monitoring and evaluation mechanism is established, centered on an integrated mine intelligence platform. This mechanism continuously collects two categories of key indicators: slope stability (e.g., displacement rate, stress changes, groundwater level) and ecological status (e.g., vegetation coverage, biodiversity, soil fertility). Through AI algorithms for continuous analysis and in-depth mining of multi-source data, regular monthly and quarterly evaluation reports are generated to accurately determine whether management and restoration effects meet standards; when indicators show abnormal fluctuations (e.g., sharp drop in vegetation coverage, accelerated slope deformation rate), the system automatically triggers a root cause investigation process, using data traceability technology to locate the problem source [11] (e.g., drought causing vegetation withering, abnormal rise in groundwater level causing slope stress imbalance), and simultaneously pushes targeted adjustment plans, achieving timely risk intervention.

A smart maintenance system is developed based on the long-term operational data accumulated by the big data platform. This system utilizes AI algorithms to achieve "predictive maintenance" and "precision conservation." For monitoring equipment such as GNSS receivers and hydrological sensors, by analyzing operational parameters like signal strength and data transmission stability, potential failures are predicted in advance, maintenance work orders are automatically generated and pushed to maintenance personnel, avoiding sudden equipment failures affecting monitoring continuity for ecological restoration areas, combined with climate data[12] (precipitation, temperature) and vegetation growth models, personalized maintenance plans (e.g., irrigation timing, fertilization cycles) are automatically generated, guiding smart irrigation equipment and drone fertilization systems to carry out precise operations, significantly reducing manual maintenance costs and resource waste.

The multi-party collaborative management mechanism is improved through the integration of resources from mining companies, research institutions, and government regulatory bodies. Using the intelligent platform to break down data silos, achieve data sharing and collaborative decision-making. Mining companies are responsible for the implementation of daily monitoring and maintenance, uploading data to the platform in real-time; research institutions rely on platform data for technology research and development, continuously optimizing AI models and management/restoration plans [13]; government regulatory bodies obtain real-time progress on mine management and restoration through the platform, conducting compliance checks and effectiveness assessments, ultimately forming a collaborative closed loop of "enterprise implementation - research support - government supervision," effectively avoiding management gaps and responsibility defaults, ensuring the effective implementation of long-term management and control.

6. Conclusion

Slope stability management and ecological restoration in open-pit mines are systematic and long-term projects, needing to address multi-dimensional challenges such as complex geological conditions, technical adaptability, later maintenance, and cost control. This paper, by combining traditional technologies with big data and AI, achieves a transition from "experience-driven" to "data-driven," from "step-by-step implementation" to "collaborative optimization," and from "short-term management" to "long-term management and control," aiming to precisely prevent risks, improve restoration effects, and ensure the sustainability of management. In the future, with the development of technology integration, greening, and standardization, mines will break through the dilemma of "development means destruction," achieving the coordinated development of "safe mining - ecological restoration - value transformation," supporting the construction of ecological civilization. Simultaneously, it is necessary to "adapt to local conditions" based on mine differences and continuously innovate and improve the technical system.

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