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Analysis of geological disaster management and ecological restoration measures in mining engineering

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Abstract. This paper provides a comprehensive analysis of the current effective measures for managing geological disasters and ecological damage caused by mining engineering development. The discussion primarily focuses on two aspects: engineering technology and ecological management. It is clear that slope stabilization technology, drainage and waterproof system construction, vegetation restoration, and artificial humidity construction play active roles in the management of geological disasters and ecological restoration in mining areas. These measures not only effectively control geological disasters but also significantly improve the ecological environment, enhance the self-recovery capacity of regional ecosystems, and achieve harmonious development of society, economy, and environment.

Keywords: Mining, Geological disaster, Ecological environment, Management, Restoration

1. Introduction

With the increasing frequency of mining activities driven by the enormous energy demands of modern cities, serious geological disasters and ecological environment damage issues have emerged. Problems such as land subsidence, landslides, soil erosion, and soil and water pollution pose significant threats to human habitation safety and ecosystem health. Therefore, exploring scientific and rational measures for managing geological disasters and restoring ecological environments in mining engineering is particularly important. By analyzing the practical application of various management technologies and ecological restoration strategies, this paper aims to provide feasible reference measures for the restoration of mining environments, with the hope of guiding the coordinated advancement of future mining development and environmental protection efforts.

2. Overview of Geological Disasters in Mining Engineering

2.1. Types of Geological Disasters in Mining

As mining activities deepen, the geological structure undergoes corresponding changes, which may lead to varying degrees of geological disasters. Common geological disasters in mining include: 1. Collapse and Landslides: This typically refers to the sudden fall of rocks or soil on steep slopes. A landslide involves the downward movement of rock and soil masses along a defined slip surface. The main causes of collapse and landslides in mining activities are the destabilization of slopes due to excessive mining, improper mining methods, and increased slope weight from water infiltration. 2. Ground Subsidence and Collapse: This occurs when cavities created by underground mining are not properly filled, causing

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the overlying strata to lose support and collapse. A significant drop in the groundwater level is also a major cause of ground subsidence, particularly common in mines where groundwater is extracted for production use. [1] 3. Debris Flows: In mining areas, especially during the rainy season, a mixture of large amounts of loose solid material and water flows rapidly along valleys or gullies, forming powerful and destructive debris flows. The causes are often related to the improper disposal of mining waste and reduced surface infiltration capacity due to vegetation destruction.

2.2. Disaster Risk Assessment Methods

To address potential disaster issues in mining, a qualitative assessment is usually conducted first. This involves subjective judgment based on expert experience and historical data on geological disasters, suitable for preliminary risk screening. Following this, a quantitative assessment is carried out based on the results and data from the initial screening. 1. Probability Analysis: This method combines historical data and statistical methods to calculate the probability of disaster occurrence, and evaluates the overall risk level by considering the severity of disaster consequences. 2. GIS and Remote Sensing Technology: By integrating geographic information systems and remote sensing data, this approach analyzes the relationship between factors such as topography, geological structure, rainfall, and disasters. It involves creating spatial risk distribution maps to visualize the potential risks. [2]

3. Analysis of the Impact of Mining Engineering on the Ecological Environment

3.1. Impact on the Natural Environment

Long-term mining activities can lead to soil degradation and pollution. During mining, surrounding surface vegetation is cleared, and heavy machinery compacts the soil, directly damaging its structure and reducing its water and nutrient retention capacity, which triggers soil degradation. Additionally, mining waste, such as tailings and waste rock, often contains heavy metals and other toxic chemicals. These can leach into the soil with rainwater, causing soil pollution. Both open-pit and underground mining require substantial groundwater extraction, which lowers the groundwater table, dries up springs, and affects the water supply in surrounding areas. Furthermore, mine water and leachate from tailings ponds may contain acidic substances, heavy metals, and chemical agents. If these are directly discharged or infiltrate the ground, they can severely pollute surface and groundwater, altering water quality.

3.2. Impact on Socioeconomic Benefits

Mining activities have comprehensive effects on residents' health, the economy, social culture, and sustainable development. Pollution of the air, water bodies, and soil not only restricts crop growth but also affects the health of nearby residents through the food chain and drinking water, increasing the incidence of respiratory and waterborne diseases. Although mining can boost the local economy and promote employment in the short term, in the long run, the resulting environmental pollution and ecosystem damage severely impact key industries such as agriculture, fisheries, and tourism, leading to land devaluation. The enormous costs of environmental restoration can further destabilize the social economy. Additionally, mining operations can damage sites of significant historical and cultural value, disrupting regional social structures and cultural heritage. In light of these challenges, it is crucial for mining activities to acknowledge the conflict with sustainable development goals. Adopting more environmentally friendly mining technologies and implementing strict environmental regulations are necessary to ensure the rational use of natural resources and the simultaneous advancement of environmental protection. This approach aims to achieve harmonious coexistence of economic prosperity, social progress, and environmental health.

4. Analysis of Technologies and Measures for Mining Geological Disaster Management

4.1. Engineering Management Technologies

4.1.1. Slope Stabilization Techniques

Slope stabilization techniques are crucial in managing geological disasters in mining, aimed at enhancing slope stability through various engineering methods to prevent collapses and landslides. The specific measures include:

1. Anchoring Technology: This includes anchor bolts (cables) and anchor net reinforcement. [3] The main idea is to utilize the tensile strength of anchor bolts, which are inserted into unstable rock and soil through drilling. One end of the anchor bolt is tightly bonded with the rock or soil, while the other end is connected to the support structure on the slope. The friction between the anchor bolt and the borehole wall, combined with the bonding force from the grouting material (such as cement slurry) injected into the borehole, work together to transfer the slope load to the deeper stable rock and soil, thereby enhancing slope stability (as shown in Figure 1). Additionally, anchor nets, composed of high-strength steel wire rope nets, steel rope anchor bolts, support ropes, pressure rings, and bases, are used. The active protection net system is installed on the surface of potentially unstable rock and soil, fixed by anchor bolts embedded in stable strata. This system intercepts and restricts rock movement through the openness of the net, while the net's tensile deformation absorbs energy and disperses the kinetic energy of the sliding rock and soil. The passive protection net is located below the slope or beside roads to intercept falling large rocks and soil, protecting lower facilities from damage. For example, in a mine in Shanxi with observed landslide risk, anchoring technology was prepared for use. Geologists first determined the slope stability and potential slip surface locations, designed the anchor bolt (cable) layout and anchor net coverage. According to the design, drill rigs drilled holes at predetermined locations, installed anchor bolts, and injected cement slurry or chemical grout to ensure a tight bond between the anchor bolts and the rock and soil. High-strength steel wire rope nets were then laid on the slope surface and fixed to the slope using anchor bolts, ensuring the net was tightly attached to the slope to effectively intercept and disperse potentially falling rocks and soil. Additionally, long-term stability can be enhanced by planting locally suitable grass seeds or shrubs on the anchor net to further stabilize the slope through plant root systems.

Figure 1. Slope anchoring techniques

2. Anti-Slide Piles and Retaining Walls: Anti-slide piles are placed at the bottom of slopes or potential slip surfaces to resist sliding through the resistance of the piles penetrating stable strata.

Retaining walls, built directly on the slope surface or at the bottom, are used to block the movement of the landslide mass, often used in suburban areas or regions with limited space.

3. Geosynthetic Materials: Geosynthetics such as geotextiles, geogrids, and geonets can increase the shear strength of slopes, prevent soil erosion, and serve as a foundation for vegetation to grow, enhancing slope stability. Geotextiles function in separation, filtration, drainage, and impermeability. They can isolate different soil layers, prevent fine soil from mixing with coarse layers, allow water flow, and reduce soil erosion. In slope protection, they act as a cover layer, reducing rainwater erosion on the slope surface and protecting the underlying structure from scouring. Geogrids, made of high-strength plastic or fiberglass, enhance the stability of foundations or slopes by dispersing external forces through their grid structure, reducing lateral soil displacement, and increasing soil shear strength and integrity.

4.1.2. Drainage and Waterproof Systems

Effective drainage and waterproof systems are essential for preventing disasters like landslides, collapses, and ground subsidence caused by groundwater activity. Proper drainage and waterproofing can control groundwater levels, reduce water pressure, and prevent water-related hazards, ensuring mine safety and surrounding environmental stability. Specific measures include: 1. Surface Drainage Systems: These involve constructing drainage ditches, catchment pools, and drainage pipelines to collect and discharge surface runoff, reducing rainwater erosion and infiltration into slopes, preventing soil erosion, and maintaining slope stability. [4] 2. Underground Drainage Measures: These include implementing drainage boreholes and infiltration wells to extract deep groundwater, suitable for areas with high groundwater levels or requiring rapid groundwater level reduction. Modern systems can incorporate water level monitoring equipment and automatic control systems to monitor groundwater level changes in real time and automatically adjust drainage flow to ensure efficient and stable operation. 3. Waterproof Systems: These involve using waterproof boards and membranes. Waterproof boards or high polymer waterproof membranes can be laid on slope surfaces or around underground structures to prevent water infiltration and protect structures from groundwater damage.

The implementation steps include conducting geological surveys to understand the distribution, flow direction, and soil permeability of groundwater in the mine to provide a scientific basis for designing appropriate drainage and waterproof systems. The systems are then custom-designed according to the geological conditions, hydrological characteristics, and disaster types around the mine to ensure they are both economical and effective. Construction quality must be strictly controlled to ensure the accurate installation of drainage pipelines, infiltration wells, and impermeable barriers, preventing system failure due to construction defects. Finally, maintenance personnel should regularly inspect and maintain the drainage and waterproof systems, clearing blockages and repairing damaged parts to ensure long-term effective operation.

4.2. Ecological Restoration Technologies

4.2.1. Vegetation Restoration and Ecological Reconstruction

Ecological restoration of mined and damaged areas begins with vegetation restoration, aimed at re-establishing plant communities and restoring ecosystem functions such as soil conservation, water retention, and biodiversity protection. Specific technical measures include: 1. Soil Improvement and Reconstruction: Mining activities often damage soil structure and deplete nutrients. Improving soil quality involves adding organic matter, mineral fertilizers, and adjusting pH levels to create favorable conditions for plant growth. 2. Selection of Local Species: Based on local climate, soil types, and native vegetation characteristics, select fast-growing, adaptable native species that can quickly form forests. Emphasize species diversity to build a stable ecosystem. Vegetation planting in mining areas should also address disaster prevention, such as landslides, collapses, and soil erosion, ensuring ecological restoration while enhancing regional safety and stability. In areas with relatively good soil conditions and gentle slopes, direct seeding is an economical and efficient choice. To strengthen surface stability, choose herbaceous and shrub species with developed root systems that grow quickly and have good soil-

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binding properties, such as perennial grasses and legumes. These plants effectively consolidate soil, reduce erosion, and their root activities help improve soil structure. In poor soil or complex terrain, planting seedlings is a more effective method (as shown in Figure 2). For steep slopes prone to landslides, select trees and drought-tolerant shrubs suitable for local conditions, such as pines, cypresses, or sumac. These plants have deep and extensive root systems that significantly enhance slope stability. Before planting, reinforce the slope with ecological grids and other engineering techniques combined with afforestation to stabilize the slope and promote vegetation recovery.

Figure 2. Afforestation for Slope Stabilization

4.2.2. Application of Ecological Engineering Technologies

Ecological engineering technologies use ecosystem principles combined with engineering measures to solve environmental pollution and ecological degradation problems. In mining management, artificial wetland treatment technologies can purify mine water bodies, construct ecological embankments and slopes to stabilize slopes and promote biodiversity, and create artificial ecosystems that simulate natural functions, such as ecological ponds for treating mine wastewater and providing habitats for aquatic organisms. Additionally, microbial remediation technologies utilize microbial metabolic activities to degrade or transform soil and water pollutants, such as heavy metals and organic pollutants. By selecting and inoculating microbial strains capable of adsorbing and transforming toxic metals in mining areas, the pollution levels in soil and water bodies can be effectively reduced. This technology needs to be combined with environmental conditions and pollutant types, using methods such as substrate optimization and microbial community construction to promote microbial activity and accelerate the remediation process.

4.2.3. Comprehensive Ecological Management Plan

For the comprehensive ecological management of a large mining area in the northwest, the following technical plan is proposed: 1. Identification and Assessment: Use drone aerial photography and remote sensing satellite images, combined with ground surveys, to precisely identify key areas such as goafs, landslide-prone areas, and severe soil erosion zones. Collect soil and water samples to analyze concentrations of heavy metals and harmful chemicals, and assess the extent of ecological system damage. [5] Conduct baseline ecological surveys to record native plant species and distributions, providing a basis for vegetation restoration. Based on the assessment results, organize meetings to discuss and formulate a comprehensive management plan that includes disaster management, ecological restoration, and community involvement, with clear phase goals and responsible parties. 2. Soil Improvement in Goaf and Waste Rock Dump Areas: Apply lime, organic fertilizers, and soil

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conditioners based on soil test reports to adjust pH levels and increase soil fertility and microbial activity. Select drought-resistant, heavy-metal-tolerant native tree species such as sea buckthorn and Chinese pistache, and mix them with herbaceous plants like fescue and bermudagrass to increase biodiversity and promote ecological balance. For slope management, use ecological bags filled with improved soil and selected grass seeds, and ecological mats pre-planted with herbaceous plants to stabilize slopes and accelerate vegetation coverage. 3. Microbial Soil Remediation: Through laboratory tests, screen microbial strains with high absorption and transformation capabilities for specific heavy metals in the mining area. Cultivate these strains to prepare microbial agents, then spray them proportionally in areas with severe heavy metal pollution. Regularly monitor soil heavy metal content and microbial community changes, adjusting application strategies based on feedback. 4. Construction of Multi-Level Artificial Wetlands: Design and build multi-level connected artificial wetlands. The first wetland filters suspended solids, followed by wetlands planted with reeds and cattails to purify water through root absorption and microbial degradation, improving water quality. Construct ecological slopes using local materials and vegetation to form natural barriers that intercept sediment and create ecological interception zones to further control soil erosion.

Figure 3. Ecological Restoration Results in Mining Areas

5. Conclusion

Through in-depth analysis and demonstration of practical cases, it is evident that the comprehensive application of modern technological methods and ecological principles, such as vegetation restoration, microbial remediation, and ecological engineering technologies, has a significant effect on restoring the ecological environment in mining areas and ensuring geological safety. Continuous monitoring, evaluation, and policy support are also key factors in ensuring the effective implementation of management measures and the sustainability of ecological restoration. Despite numerous challenges, by adopting targeted, scientific, and reasonable management strategies, it is possible to effectively promote the ecological recovery of mining areas and pave the way for achieving the dual goals of mining development and environmental protection.

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