Sustainability in Environment
ISSN 2470-637X (Print) ISSN 2470-6388 (Online)
Vol. 11, No. 3, 2026
www.scholink.org/ojs/index.php/se

Original Paper

Mine Geological Environment Problems and Ecological Restoration Measures of Longlei Lead-Zinc Deposit in Gongcheng, Guangxi

Qin Yuanxiang[1], Li Yuanqiang[1], Wei Changpei[1], & Zhang Zhan[1]
[1] Guangxi Zhonghui Resource Technology Industry Limited company Guilin, Guangxi 541004, China

Received: June 07, 2026 Accepted: July 09, 2026 Online Published: July 20, 2026
doi:10.22158/se.v12n3p152 URL: http://dx.doi.org/10.22158/se.v12n3p152

Abstract
The exploitation of mineral resources provides crucial material support for regional economic development, yet the concomitant mine geological environmental issues have become core constraints restricting the sustainable development of the mining industry. The Longlei Lead-Zinc Deposit is situated in the Laochang lead-zinc ore field in the western segment of the Nanling Metallogenic Belt, representing a typical small-to-medium-sized lead-zinc deposit in this region. Taking this deposit as a research case, this paper systematically elaborates the geological environmental background of the mining area through field geological surveys and comprehensive indoor data analysis. It accurately identifies dominant geological environmental hazards induced by mining activities, including geological disasters, topographic and geomorphic landscape destruction, water-soil environmental pollution, and land resource degradation. A targeted classified technical system for ecological restoration is accordingly established. The research outcomes can effectively restore the ecological structure and functions of the mining area, rebuild ecological balance, facilitate sound, coordinated and sustainable evolution of the mine geological environment, and offer a replicable and scalable practical paradigm for geological environmental protection and ecological restoration of analogous lead-zinc deposits.

Keywords
Geological Environment, Ecological Restoration, Longlei Lead-Zinc Mine, Gongcheng, Guangxi

1. Introduction

Mineral resources constitute an essential material foundation for national economic and social development. While long-term large-scale mining boosts regional economic growth, it continuously disturbs and damages the geological environment of mining areas and surrounding zones. Prominent manifestations include aquifer destruction, topographic and geomorphic landscape degradation, water-soil environmental pollution, and frequent geological disasters such as collapse, landslide, ground subsidence and debris flow[1][2]. These hazards severely threaten regional ecological security and residential environmental quality, and hinder the progress of ecological civilization construction. Domestic scholars have carried out extensive research on mine geological environment governance and proposed a series of prevention, control and restoration schemes[3][4]. Nevertheless, significant heterogeneity exists among individual mines in terms of geological conditions, mining technologies and environmental impacts, leading to drastic disparities in the type, development intensity and influence scope of geological environmental problems. Therefore, governance and restoration measures must be dynamically optimized according to actual mine conditions to ensure scientificity, pertinence and effectiveness[5][6]. Accordingly, systematic analysis of geological environmental problems and precise ecological restoration research on typical mines serves as a vital approach to break the bottleneck of ecological restoration for regional similar mines and improve relevant technical systems.

The Longlei Lead-Zinc Deposit is located in Limu Town, Gongcheng Yao Autonomous County, Guangxi Zhuang Autonomous Region. Discovered in 1958, it is a typical small underground mining deposit within the Laochang lead-zinc ore field of the western Nanling Metallogenic Belt. Existing research predominantly focuses on geological characteristics and metallogenic genesis of this deposit[7], while studies on identification, assessment and ecological restoration of its geological environmental problems remain blank. Based on field geological investigations, this paper systematically collects geological environmental background data of the mining area, comprehensively investigates geological environmental problems triggered by mining activities, thoroughly analyzes the genesis and development characteristics of these problems by integrating practical ecological restoration experience in and around the mining area, and further puts forward targeted ecological restoration measures. This study fills the research gap regarding geological environment of the Longlei Deposit, and provides theoretical references and practical basis for geological environmental protection and ecological restoration of analogous lead-zinc deposits.

2. Geological Environmental Conditions of the Mine

2.1 Natural Overview of the Mining Area

The Longlei Lead-Zinc Deposit lies in Longlei Hamlet, Dajian Village, Limu Town, Gongcheng Yao Autonomous County, Guilin City. The mining area belongs to the medium-low mountain subregion of tectonic denudation landform, featured by an overall west-high-east-low terrain with intense topographic fluctuation and V-shaped steep gullies. The region is dominated by central subtropical monsoon climate with uneven temporal-spatial rainfall distribution. Floods concentrate in spring and summer, accompanied by frequent rainstorms in early summer; alternating prolonged droughts and heavy rainstorms easily trigger geological disasters such as collapse and landslide.

Surface water in the mining area is primarily recharged by atmospheric precipitation. Runoff from all open sites naturally drains to adjacent low-lying areas following terrain gradients. Major surrounding surface water systems include Juanlongmiao Gully, Huangzhu River and Leiming River. All mining sites are distributed above the local erosion base level, presenting favorable natural drainage conditions.

2.2 Stratigraphy and Lithology

Exposed strata in the mining area mainly consist of the Qingxi Formation of Cambrian, the Lower Devonian Lianhuashan Formation and Quaternary overburden, with lithological characteristics described as follows:

Third Lithologic Member of Cambrian Qingxi Formation (ϵq^3): Light gray thin-to-medium thick layered low-metamorphic dolomitic fine sandstone interbedded with sericite slate. The fine sandstone is hard and brittle, prone to fragmentation under tectonic action; sericite slate develops well-defined bedding planes with variable occurrence.

First Member of Lower Devonian Lianhuashan Formation (D_1l^1): Distributed in the central and south-central mining area, unconformably overlying Cambrian strata. It is a heteroclastic rock series composed of glutenite, sandstone, siltstone, mudstone and minor carbonate rock, with gentle stratum occurrence.

Quaternary System: Dominated by humus soil and gravel-bearing silty clay. Humus soil covers the surface of vegetation-covered zones, with thickness ranging from 0.1 m to 0.3 m; gravel-bearing silty clay represents weathered residual-slope deposits, with thickness of 0.5–3.0 m and heterogeneous soil texture, appearing loose near the ground surface.

2.3 Geological Structure and Seismicity

The mining area is located within the Haiyangshan Uplift of the Guilin-Guangdong Depression in the Central-Guangxi Platform of the South China Paraplatform, inside the Laochang Dome and on the southern limb of the Gaoshanding Anticline. Regional structural lines are predominantly near north-south, followed by northeast orientations. Secondary folds are extensively developed within the zone, leading to highly variable stratum occurrence. Two major fault groups are identified: Northeast-trending tensional-torsional normal faults arranged in en echelon pattern, serving as primary ore-controlling structures; Near north-south tensional-torsional fractures that control the distribution of river systems. Most faults feature multi-stage activity and well-developed fracture zones. The region falls within a low-intensity seismic tectonic zone in northeastern Guangxi, with no historical records of destructive earthquakes. The peak ground acceleration is 0.05g, characteristic period 0.35s, seismic basic intensity Grade VI, and the crust is sub-stable.

2.4 Hydrogeological Conditions

Groundwater types in the mining area include pore water in loose deposits and fracture water in clastic rocks, predominantly recharged by infiltration of atmospheric precipitation. Quaternary pore water discharges locally or replenishes bedrock fracture water, which further flows to deep groundwater.

Faults exhibit water-resisting properties, yet fractured rock masses within fault influence zones possess high permeability, with partial old mine water accumulation resulting in moderate water inrush risk.

Mine water inflow varies drastically with seasons: normal inflow ranges from 81.88 m^3/d to 420.42 m^3/d, while flood-period inflow reaches 245.64–1261.26 m^3/d. Mining zones are situated above the erosion base level with sound natural drainage, and underground mining and dewatering drainage pose low risks to major regional aquifers. The hydrogeological complexity of the mining area is classified as moderate.

2.5 Engineering Geological Characteristics

Rock and soil masses in the mining area are divided into single-layer cohesive soil mass and clastic rock engineering geological rock group. Surrounding rocks mainly include dolomitic fine sandstone, sericite slate, glutenite and siltstone with weak alteration and fracture development, and local weak interlayers. The rock mass has low weathering degree with saturated uniaxial compressive strength of 60–131 MPa, leading to overall favorable stability of ore body roof, floor and surrounding rocks. Only local roof caving and shaft wall collapse risks exist in underground mining tunnels. Foundation stability of engineering sites is sound, yet partial artificial slopes are characterized by fractured rock masses and loose structures with instability hazards. The engineering geological complexity is moderate.

2.6 Comprehensive Assessment of Mine Geological Environment

Synthesizing geological background, hydrogeology, engineering geology, geological disasters and mining disturbance factors, the overall geological environmental complexity of the mining area is classified as complex: geological background, hydrogeological and engineering geological conditions are moderate, while geological structures and topography-geomorphology are complex. Based on the importance of the assessment zone and mine construction type, the mine geological environmental impact assessment grade is Grade I, and the geological disaster risk assessment grade is Grade II.

3. Geological Environmental Problems of the Mine

The Longlei Lead-Zinc Mine is a small underground mining mine. Pre-mining construction facilities include an explosive depot, No.1–No.6 waste rock dumps, living quarters, borrow pits and mine roads. Geological environmental problems induced by mining concentrate on waste rock dumps and road corridors, falling into four categories: geological disasters, topographic-geomorphic landscape destruction, land resource degradation, and water-soil environmental pollution. Owing to limited goaf scale and horizontal adit mining, disturbance to aquifer structures is minor and not elaborated in this paper.

3.1 Geological Disasters

3.1.1 Existing Geological Disasters

Instability of artificial slopes: Ten artificial slopes formed by waste rock stacking and road excavation feature fractured rock masses, developed joints and loose slope surfaces with obvious local rockfall and soil erosion, presenting an overall sub-stable state. Collapse and landslide are prone to occur under heavy rainfall and excavation disturbance, representing strongly developed geological hazards.

Small-scale collapse: Two typical small collapses are identified in the mining area (Fig.1), both triggered by cut slopes constructed for mine roads. Unloading free faces formed at slope toes induce small-scale collapses under rainfall scouring and self-weight of rock-soil masses, with collapse volume ranging from 15.0 m³ to 17.5 m³, classified as small-scale collapses. Existing collapse hazards are strongly developed, without casualties or property losses reported.

Figure 1. Field Photographs of Collapse B1 and B2

3.1.2 Predicted Geological Disasters

Combined with mining methods, topographic-geological conditions and engineering activities, four types of geological disasters-unstable slopes, goaf ground subsidence, debris flow and collapse-are predicted to occur or intensify within the mining area. The overall occurrence probability ranges from medium to high, hazard degree from minor to moderate, and risk grade is medium. Tab.1 summarizes development characteristics and risk analysis of each disaster type.

Table 1. Characteristics of Existing and Predicted Geological Disasters

Disaster Type	Location	Analysis of Development Discriminant Indicators	Inducing Factors	Threat Condition	Occurrence Probability	Hazard Degree	Risk Grade
Unstable Slope	No.1–No.6 waste rock dumps, mine roads, horizontal adit portals	Slope height 3-143 m, gradient 40°–60°, composed of dolomitic fine sandstone, sericite slate, weathered layer, waste rock and clay. No.1–No.6 waste rock dumps, mine roads and adit portals fall within the influence range of unstable slopes.	Artificial excavation & filling disturbance, vibration, surcharge; secondary factors: precipitation, temperature variation	Threatens 5–8 people, potential direct economic loss 500,000–900,000 CNY	High	Minor	Medium

	Borrow pits	Cut slopes 6–8 m high with slope angle 55°, slope ratio 1:0.7. Based on accumulation soil type and slope height 5-10 m, medium probability of collapse and landslide is determined.	Artificial excavation disturbance, vibration; natural rainfall, temperature variation	Threatens 5-8 people, potential direct economic loss 500,000-900,000 CNY	Medium	Minor	Medium
Goaf Ground Subsidence	No.1–No.2 & No.5–No.6 waste rock dumps, borrow pits, mine roads	Height of water-conducting fractured zone: 12.92–24.70 m; height of caving zone: 5.17–14.86 m; maximum subsidence value 60.21 mm, maximum tilt value 8.28 mm/m, maximum horizontal displacement 18.06 mm, maximum horizontal deformation 3.78 mm/m.	Mining, water pumping & drainage, excavation disturbance, surcharge	Threatens 5–8 people, potential direct economic loss 500,000–900,000 CNY	High	Minor	Medium
Debris Flow	No.1–No.6 waste rock dumps, living quarters, mine roads	Loose rock-soil materials generated by mining have low stability coefficients. Long-duration heavy rain leads to rapid surface runoff converging on loose material sites, saturating soil mass and triggering fluid flow, forming favorable conditions for debris flow. Comprehensive quantitative score of debris flow development reaches 89.	Artificial waste rock surcharge, vegetation destruction, rainfall	Threatens 10–15 people, potential direct economic loss 2,000,000–3,000,000 CNY	Medium	Medium	Medium
Collapse	No.3 waste rock dump, mine roads	Slope height 3–15 m, gradient 40°–50°, composed of dolomitic fine sandstone, sericite slate, weathered layer and clay. No.3 waste rock dump and mine roads lie within unstable slope influence zones.	Artificial excavation & filling disturbance, vibration, heavy rainfall	Threatens 5–8 people, potential direct economic loss 500,000–900,000 CNY	High	Minor	Medium

3.2 Topographic-Geomorphic Landscape Destruction and Land Degradation

No major transportation trunk lines, buildings, water sources, cultural relics or scenic spots exist within a 500 m radius of the mining area. Nevertheless, mining activities inflict relatively severe damage to regional topographic-geomorphic landscapes and land resources, manifested as follows:

Landscape incoherence of waste rock dumps: Excavation waste rock is stockpiled in open air at

No.1–No.6 dumps without effective disposal. Slopes formed by downslope waste rock dumping create stark color contrast with surrounding natural mountain vegetation, damaging original topography and resulting in extremely poor landscape coordination.

Loss of land functions: Waste rock overburden completely eliminates original land functions. Stockpiles consist of fragmented waste rock with harsh soil conditions that hinder natural vegetation recovery, imposing high land reclamation difficulty. Land occupation by explosive depots, office buildings and living quarters also causes vegetation destruction and land resource degradation.

Topographic damage from excavated slopes: Borrow pits and mine road excavation generate steep rock-soil slopes 6–10 m high with gradient 55°–60°, directly destroying original topography, degrading surrounding land resources and exacerbating soil erosion risks.

In summary, mining activities cause relatively severe damage to both topographic-geomorphic landscapes and land resources within the mining area.

3.3 Water-Soil Environmental Pollution

Water-soil environmental pollution refers to chemical contamination of surrounding surface water and land resources induced by mining operations[8]. Under rainfall leaching, sulfide oxidation in ore and surrounding rock may trigger water acidification and heavy metal release. Direct discharge of untreated mine drainage and leachate will pollute water and soil environments, inhibiting soil organisms and vegetation growth. Field testing of water and soil samples indicates all indices comply with national standards; waste rock is classified as general industrial solid waste without toxicity, and mining activities impose mild pollution on water-soil environments.

4. Ecological Restoration Measures for the Mine

Centered on four core objectives-disaster prevention and mitigation, geomorphology restoration, soil and water conservation, and vegetation revegetation-this research follows the principles of local adaptation, classified governance, ecological priority and sustainable development. Targeted systematic ecological restoration measures including geological disaster control, topographic remediation, land reclamation, vegetation restoration and water-soil pollution prevention are implemented for distinct sites (waste rock dumps, explosive depots, living quarters, borrow pits, horizontal adits and air shafts) to restore the ecological structure and functions of the mining area and advance green mine construction. Mine roads are retained as forest management passages with well-developed vegetation on both sides capable of natural soil erosion control, requiring no supplementary planting.

4.1 Ecological Restoration Measures for Waste Rock Dumps

To address slope instability, topographic damage and land occupation at No.1–No.6 waste rock dumps, an integrated restoration workflow of "cleanup – retaining support – drainage – land leveling – soil covering – fertility improvement – afforestation" is adopted (Fig.2). Detailed procedures are specified below:

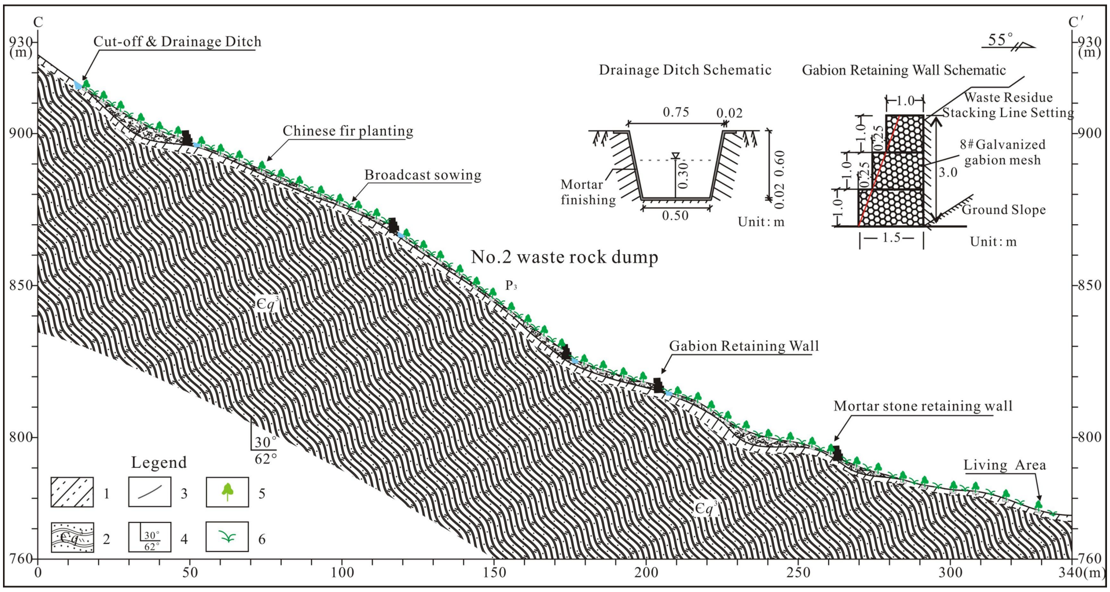

Figure 2. Cross-section Profile of Waste Rock Dump Treatment Engineering

1. Residual-slope silty clay; 2. Low-metamorphic dolomitic fine sandstone of the 3rd Member, Cambrian Qingxi Formation; 3. Terrain line / original terrain line; 4. Stratum occurrence; 5. Chinese fir planting; 6.Broadcast sowing

Waste rock cleanup: Stockpiled waste rock is cleared and transported outward for comprehensive utilization as aggregate for concrete mixing stations and roadbed backfill materials. Slopes formed by waste rock accumulation are trimmed and cleaned to basically restore original topography.

Retaining wall construction: A composite support system combining mortar stone gravity retaining walls and gabion mesh retaining walls is built at the base of waste rock dumps. Gravity mortar stone retaining walls feature 4.0 m base width, 2.0 m top width, 5.0 m wall height and 2.0 m foundation burial depth, with two rows of drainage pipes and matched filter layers embedded in walls. Gabion mesh retaining walls have 1.0 m top width, 1.5 m base width, 3.0 m height and 0.50 m foundation burial depth, with cross-sectional area of 3.75 m².

Interception and drainage ditch construction: Taking micro-topographic watersheds around waste rock dumps as runoff boundaries, the catchment flow formula for small drainage areas is applied to calculate surface runoff and determine cross-sectional dimensions and flow capacity of ditches. Interception and drainage ditches are arranged at the top, periphery and interior of waste rock dumps with 2.0 cm thick cement mortar three-side plastering to mitigate water scouring.

Land leveling: Mechanical and manual combined operations are adopted to level reclamation zones of waste rock dumps, with leveling elevations rationally adjusted based on original terrain.

Soil covering and fertility improvement: Reclamation zones are planned as arbor forest land, covered with 0.6 m thick clay (5% transport loss rate reserved). Compound fertilizer is uniformly spread on the surface at a dosage of 300 kg/hm² to improve soil fertility.

Arbor-shrub-grass revegetation: A mixed planting mode of Chinese fir + Pennisetum alopecuroides is adopted. Chinese firs are planted in pits at a density of 1 plant per 6 m²; Pennisetum alopecuroides seeds are broadcast between trees for rapid revegetation and soil erosion control. A 5.0 cm thick straw/thatch mulch is laid around tree roots to retain moisture and resist cold, improving seedling survival rate.

4.2 Ecological Restoration Measures for Explosive Depot and Living Quarters

Targeting building occupation, ground hardening and vegetation destruction at explosive depots and living quarters, the restoration workflow "demolition – debris clearance – leveling – deep tillage – fertility improvement – cash forest planting" is implemented:

Masonry demolition: After mining completion and equipment removal, excavators demolish ground buildings. Demolition volume is estimated at an average thickness of 0.20 m³/m², and construction waste is transported to goafs for backfill utilization.

Hardened layer removal: Mechanical operation eliminates ground hardened layers, with engineering volume estimated at average thickness of 0.15 m; removed materials are uniformly conveyed to goafs as backfill.

Site leveling and deep tillage: Mechanical-manual integrated leveling is conducted for reclamation zones with elevations determined by field terrain. The zone is plowed to a depth of 0.30 m after leveling to enhance soil aeration and permeability.

Soil fertility improvement: Compound fertilizer is evenly spread on plowed ground at 300 kg/hm² to ameliorate soil structure and fertility.

Citrus planting: The original site is reclaimed as cash forest land with citrus planted in pits at a density of 1 plant per 4 m². A 5 cm thick straw mulch is laid around root systems to raise seedling survival rate, balancing ecological restoration and economic benefits.

4.3 Ecological Restoration Measures for Borrow Pits

For excavated slopes, land degradation and vegetation deficiency at borrow pits, the workflow "leveling – deep tillage – fertility improvement – arbor-grass revegetation" is adopted:

Site leveling: Mechanical operations flatten borrow pit zones and adjust elevations to form gentle slopes, eliminating slope instability hazards and creating favorable conditions for vegetation recovery.

Deep tillage: The entire zone is plowed to 0.30 m depth after leveling to improve soil cultivability.

Soil fertility improvement: Compound fertilizer is spread on soil surface at 300 kg/hm² to meet plant growth nutrient demands.

Arbor-grass revegetation: Consistent with waste rock dumps, the mixed Chinese fir + Pennisetum alopecuroides mode is adopted. Chinese firs are pit-planted at 1 plant per 6 m² with grass seeds broadcast between trees; 5 cm straw mulch covers root zones for moisture and cold preservation.

4.4 Ecological Restoration Measures for Horizontal Adits and Air Shafts

To address goaf connectivity and slope instability hazards of horizontal adits and air shafts, an integrated workflow of "permanent plugging – revegetation – safety warning" is implemented. All adits and air shafts are permanently sealed to a depth of 20 m upon mining completion, with detailed construction techniques as follows:

Horizontal adit plugging: A 1.0 m thick mortar stone sealing wall is built 20 m inward from adit portals, followed by backfilling 18.0 m thick clay toward the portal, and a final 1.0 m thick mortar stone sealing wall at the portal. After plugging, climbing plants are cultivated around adit portals for revegetation, and safety warning signs are installed.

Air shaft plugging: A 1.0 m thick mortar stone sealing wall is constructed 20 m inward from the shaft head with its foundation embedded 0.5 m into shaft walls to enhance stability. The shaft is backfilled with 18.0 m thick clay toward the shaft head, capped by a 1.0 m thick mortar stone sealing wall. Post-plugging revegetation is realized via tree planting and grass seed broadcasting around the shaft head, accompanied by safety warning signs.。

4.5 Prevention and Control Measures for Water-Soil Environmental Pollution

Given the mild pollution degree of water and soil in the mining area, a prevention system of "source control – wastewater treatment – cyclic utilization" is adopted to reduce pollution at source and realize efficient water resource utilization:

Cyclic utilization of mining wastewater: Underground mining wastewater and mine water inflow converge along drainage ditches in horizontal roadways via gravity flow. After oil separation, sedimentation and clarification treatment, the treated water is transported to stopes and tunneling working faces through seamless steel pipes for production operations, fire protection and dust suppression.

Discharge of comprehensively treated wastewater after reaching standards: Mine drainage and waste rock leachate in the mining area converge into a wastewater treatment station through collection systems. After treatment, disinfection and compliance testing, the effluent is reused for underground and ground dust suppression and greening irrigation; residual wastewater undergoes advanced treatment to meet discharge standards before converging with surface water bodies.

Centralized treatment of domestic sewage: Canteen wastewater and mechanical maintenance wastewater receive pre-oil-separation treatment, then mixed with other domestic sewage into integrated wastewater treatment facilities adopting biological contact oxidation, phosphorus and nitrogen removal processes to guarantee effluent compliance before discharge.

Source anti-seepage control of solid waste: Ores and waste rock are centrally stockpiled in designated exclusive zones with anti-seepage liners laid at the bottom of stacking areas to prevent leachate infiltration and subsequent soil and groundwater pollution.

4.6 Discussion on Ecological Restoration Effects

Systematic implementation of the above ecological restoration measures can effectively mitigate geological environmental problems and gradually restore the ecological structure and functions of the mining area, with core implementation effects summarized as follows:

Effective prevention and control of geological disasters: Construction of retaining walls and interception ditches fundamentally eliminates hidden hazards including slope instability, collapse and debris flow. Goaf backfilling and permanent plugging of adits and air shafts reduce goaf subsidence risks, safeguarding production and living safety of the mining area and surrounding residents.

Restoration of topographic-geomorphic landscapes: Waste rock clearance, building demolition and site leveling effectively restore original mine topography, eliminate landscape incoherence between waste rock piles/hardened ground and natural surroundings, and reconstruct regional landscape integrity.

Efficient control of water-soil pollution: Wastewater centralized treatment, cyclic utilization and anti-seepage measures for solid waste stockpiles reduce water-soil pollution at source, stabilize water-soil environmental quality of the mining area and avoid pollution expansion.

Reconstruction of ecosystem functions: Vegetation restoration via arbor-grass mixed planting and cash forest cultivation effectively increases vegetation coverage in the mining area, alleviates soil erosion, improves soil conditions, creates suitable habitats for flora and fauna, and promotes virtuous cycles of the ecosystem.

Efficient utilization of land resources: Land reclamation transforms degraded land into arbor forest and cash forest land, realizing land resource reuse and balancing ecological and economic benefits, advancing coordinated development of mining industry and ecological environment.

The ecological restoration framework proposed in this research takes geological disaster control as the foundation, topographic remediation and vegetation revegetation as core tasks, and water-soil pollution prevention and cyclic land utilization as supporting guarantees. It organically integrates disaster prevention, ecological restoration, land utilization and environmental protection, drives the mine geological environment toward healthy, coordinated and sustainable evolution, and lays a solid foundation for green mine construction.

5. Conclusions

Taking the Longlei Lead-Zinc Deposit in Gongcheng, Guangxi as the research object, this paper sorts out the geological environmental background of the mining area through field surveys and indoor comprehensive analysis, identifies core geological environmental problems, and proposes targeted ecological restoration measures. The primary conclusions are drawn as follows:

1. The overall geological environmental complexity of the Longlei Lead-Zinc Mine is classified as complex. Geological background, hydrogeological and engineering geological conditions are moderate, while geological structures and topography-geomorphology are complex. The mine geological environmental impact assessment grade is Grade I, and geological disaster risk assessment grade is Grade II.

2. Core environmental problems induced by mining operations include strongly developed geological disasters (slope instability, collapse, potential subsidence and debris flow), relatively severe topographic-geomorphic and land degradation, and mild water-soil environmental pollution, concentrated within waste rock dumps and road corridors.

3. A zoning and classified precise restoration technical system is established: waste rock dumps adopt the "cleanup – retaining support – revegetation" model; building zones adopt the "demolition – reclamation – cash forest" model; borrow pits adopt the "leveling – fertility improvement – revegetation" model; underground openings adopt the "plugging – revegetation – warning" model; full-area wastewater circulation and pollution source control are implemented, forming scientifically feasible engineering measures.

4. Implementation of the proposed ecological restoration scheme can effectively prevent geological disasters, remediate damaged landscapes and land resources, control water-soil pollution and reconstruct ecosystem functions, facilitating healthy, coordinated and sustainable evolution of the mine geological environment.

This study fills the research gap regarding geological environment and ecological restoration of the Longlei Lead-Zinc Mine, provides theoretical references and engineering paradigms for geological environmental protection, disaster prevention and ecological restoration of small-to-medium lead-zinc deposits in South China, and bears vital significance for promoting green development of regional mining industries and safeguarding regional ecological security.

Acknowledgements

We sincerely appreciate the leadership and engineering technical staff of Gongcheng Daoping Lead-Zinc Mine Co., Ltd. for their strong support and professional guidance during field investigations.

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