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A Review of Ecological Restoration Technologies for Excavated Slopes in Hydropower Projects

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Abstract: Excavation and construction of hydropower projects easily trigger ecological problems such as exposed slope rock masses, soil water loss, and sharp decline of biodiversity. Traditional rigid protection modes deliver poor ecological benefits. This paper systematically analyzes ecological damage on excavated slopes of hydropower projects, sorts out the process characteristics and application scopes of three mainstream ecological restoration technologies: vegetation concrete slope protection, three-dimensional net grass planting, and lattice beam combined with revegetation. The application effects of various technologies are verified through practical engineering cases, and the industry development trends of collaborative safety governance, native vegetation construction, as well as the integration of low-carbon and intelligent technologies are concluded. The research aims to define the application scope of different restoration technologies and provide a scientific basis and technical references for the design and construction of ecological restoration schemes for hydropower project slopes.

Keywords: Hydropower project; Excavated slope; Ecological restoration; Restoration technology

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1. Introduction

Most hydropower bases in China are located in mountain valley zones. Driven by the green energy transition, hydropower projects keep advancing. Mountain excavation generates a large number of high, steep, exposed slopes. Original soil layers and vegetation systems are destroyed, which readily gives rise to soil water loss, rock mass collapse, and damage to biological habitats. Early governance mostly adopted rigid protection measures such as stone masonry and concrete, which could only satisfy slope stability requirements but failed to restore regional ecological connectivity. With the continuous advancement of ecological civilization construction, the concept of engineering governance has shifted from focusing merely on structural safety toward emphasizing ecological reconstruction. Slope restoration difficulty varies greatly under different climate zones and lithological conditions. Various ecological restoration technologies have emerged, yet

systematic summaries concerning their application scope and long-term community maintenance effects are still insufficient. Therefore, sorting and summarizing ecological restoration technologies for excavated slopes of hydropower projects can provide a theoretical basis for engineering practices.

2. Main characteristics of ecological damage on excavated slopes of hydropower projects

Ecological damage on excavated slopes of hydropower projects features typical compound attributes. Earth-rock excavation strips original soil and vegetation, leaving large areas of exposed rock masses. Slope surface soil mass structure is fragmented, and soil water retention and fertilizer holding capacity drop substantially, so native vegetation communities lose survival substrates. Most slopes are steep, with strong runoff scouring and high risks of soil water loss. Rock masses with developed fractures are prone to weathering, spalling, and shallow sliding [1]. Blockage of regional biological corridors leads to increasing fragmentation of habitats for local animals and plants, and continuous decline of biodiversity. Disturbed slopes witness changes in microclimate; light and humidity conditions are unfavorable for natural vegetation recovery, and ecosystems require a long restoration cycle via natural succession. Superposition of human engineering disturbance and geological deterioration results in damaged slopes with unstable structures and missing ecological functions, raising implementation difficulties for ecological reconstruction.

3. Current mainstream slope ecological restoration technologies and their application features

3.1. Vegetation concrete slope protection restoration technology

The vegetation concrete slope protection technology adopts special revegetation substrates. Soil, organic matter, slow-release fertilizer, binder, and plant seeds are mixed and sprayed onto rock slopes to form a hardened revegetation layer with anti-scouring capacity and conditions for vegetation growth. This technology is applicable to high, steep, rocky excavated slopes. The substrates feature good integrity, can resist storm runoff scouring, and effectively prevent rock mass weathering spalling. It requires strict substrate proportioning, results in poor initial slope surface air permeability, and entails high construction costs. It is mostly applied to permanent rocky slopes with large gradients requiring long-term protection in hydropower projects. Later-stage monitoring shall be carried out on vegetation community succession to prevent cracking and falling off of surface substrates [2].

3.2. Three-dimensional net grass planting ecological restoration technology

The three-dimensional net grass planting technology uses polymer three-dimensional geonet mats as slope surface fixing carriers. Planting soil and plant seeds are filled into the net mats. The three-dimensional net structure fixes surface soil and provides support for herb rooting. This technology features simple construction procedures and low project cost, and delivers good slope surface water permeability. It applies to soil slopes or strongly weathered rocky slopes with gentle gradients [3]. Geonet mats have an upper limit for anti-aging service life. They tend to age and get damaged under long-term exposure and show weak resistance against heavy rainfall scouring, so they cannot be independently adopted for high steep rocky slopes. They are mostly used for shallow protection of spoil heap slopes and gently excavated surfaces in

hydropower projects, and native herbs are preferred to build simple vegetation systems [4].

3.3. Lattice beam combined with revegetation composite restoration technology

The composite restoration technology of lattice beam plus revegetation is a compound scheme integrating engineering reinforcement and ecological reconstruction. Concrete or stone masonry lattice beams are used to anchor and partition slope rock masses to reduce landslide risks. Revegetation substrates are backfilled inside lattice frames for plant cultivation [5]. Lattice systems can bear the stress of slope rock and soil masses and realize both deep-layer stabilization and surface-layer ecological restoration. It is suitable for medium to high steep slopes with complex lithology and hidden shallow sliding risks. Nevertheless, lattice construction involves large-volume work and high requirements for slope surface flatness. Hardened lattice parts split slope surface ecological spaces; vegetation can only grow inside frames, leading to poor ecological connectivity. It is widely applied to key excavated slopes with high stability risks in hydropower projects [6].

4. Analysis on application trends of ecological restoration technologies for excavated slopes of hydropower projects

4.1. Collaborative development of ecological engineering safety

Traditional slope governance separates rock-soil stability from ecological restoration. Rigid protective structures cut off slope surface material circulation and cannot generate long-term ecological benefits. Current technological development realizes in-depth integration of engineering reinforcement measures and ecological reconstruction systems. On the premise of guaranteeing bottom-line safety for slope anti-sliding and anti-scouring performance, layout modes of protective structures are optimized, and the proportion of hardened base surfaces is reduced. Governance schemes no longer merely attach importance to short-term slope greening effects. They also take long-term rock-soil stability, soil water conservation, and restoration of ecological functions into consideration. An evaluation system linking safety assessment with ecological effect evaluation is established, so as to mitigate secondary geological disaster risks induced by engineering disturbance and achieve long-term coordinated operation of slope protection functions and ecological service functions [7].

For instance, in the “Excavated Slope Governance Project of a Hydropower Project on the Upper Jinsha River,” the project developer, together with scientific research institutes, carried out collaborative design practices for stabilization and ecological restoration of high steep rocky slopes. After excavation, the maximum slope height reached 180 meters. Rock masses featured well-developed joints and fractures with partial shallow sliding risks. The original scheme only adopted anchor cable frame protection, leading to a high proportion of hardened slope surfaces and difficulties in vegetation restoration. The technical team readjusted governance ideas, optimized frame beam spacing, and reduced the area occupied by concrete structures, reserving revegetation spaces inside frames. Rock mass anchoring, fracture sealing, and revegetation substrate spraying were implemented simultaneously in the construction phase. Verification results of rock-soil stability served as preconditions for vegetation allocation, and ecological restoration schemes could not lower slope anti-sliding safety reserves. Joint monitoring sites were set up during construction to observe rock mass displacement, slope surface runoff, and soil erosion rates. Geological safety monitoring data were incorporated into the evaluation system for ecological restoration effects. After governance, the overall slope stability coefficient meets specification requirements; slope surface vegetation

coverage rises from the original 70% to over 85%, and runoff scouring intensity drops significantly. Abandoning the traditional separate implementation mode of safety protection and ecological reconstruction, this project adopts an integrated design philosophy to balance structural reinforcement and vegetation growth demands, avoids ecological isolation caused by rigid protection, and provides a referable engineering paradigm for slope governance of hydropower projects in deep cut gorge areas.

4.2. Multi-component construction of native vegetation communities

Early slope ecological restoration mostly adopted fast-growing exotic herbs, resulting in simple community structures, vegetation premature senescence and degradation, and failure to form stable slope surface ecosystems. Current restoration ideas have shifted from engineering-oriented approaches toward priority allocation of native species. Local arboreal, shrub, and herb components adapted to slope site conditions are selected according to regional climate and soil conditions to form multi-layer compound vegetation communities [8]. Species selection shall consider interspecies symbiotic relationships to improve community drought and waterlogging resistance and lower later-stage maintenance costs. Native vegetation can adapt to local food chain structures, facilitate habitat restoration for animals and plants, improve the self-sustainability of slope ecosystems, and drive restored slopes to gradually evolve toward natural primary ecosystem states [9].

For example, in the "Ecological Restoration Project for Excavated Spoil Heap Slopes of a Hydropower Station on the Middle Dadu River," the general contractor, in cooperation with local forestry scientific research institutions, carried out allocation tests for native plant communities and long-term succession regulation. The project area features a dry, hot valley climate with strong evaporation and thin soil layers. Fast-growing exotic herbs were adopted in early stages, leading to large-scale degradation three years later and partial slope surface soil water loss. Technical personnel conducted field surveys on local native shrub and herb communities and selected drought-tolerant and barren-resistant native arbor, shrub, and herb species, including *Terminalia franchetii*, *Dodonaea viscosa*, and *Pennisetum alopecuroides*. The single herb planting mode was discarded to build multi-layer compound vegetation systems. In the construction phase, site units were divided according to slope microtopography: drought-tolerant shrubs were planted first on steep sections, while herbs and seedlings were allocated on gentle sections. Planting density was adjusted to reduce interspecies competition. The project reduced application of external fertilizers and relied on litter to gradually form slope surface humus layers, lowering later-stage maintenance workload. Vegetation growth was observed for five consecutive years; community species diversity increased year by year, with native plant proportion exceeding 90 %, and slope surface vegetation structures approximated local natural communities. This project constructs stable ecosystems dominated by native species, weakens artificial maintenance intervention, improves slope ecosystems' capacity to resist extreme drought weather, and solves engineering problems of premature senescence and degradation of vegetation on dry hot valley slopes.

4.3. Integration of low carbon materials and intelligent monitoring

Research and development of slope restoration materials are gradually oriented toward low energy consumption and environmentally friendly directions. Solid waste recycled substrates and biological binders partially replace high-carbon concrete products to reduce carbon emissions from engineering construction. Information technology is gradually applied to slope operation and maintenance. Sensors are installed on restored slopes to collect data such as slope surface displacement, soil moisture content, and vegetation growth status, so as to build slope ecological monitoring systems. Restoration effects are evaluated in

real time according to monitoring data, and hidden dangers such as substrate peeling off and vegetation degradation are responded to promptly, linking engineering progress with later-stage management and protection. The integration of low-carbon materials and intelligent monitoring technologies transforms slope ecological restoration from experience-driven governance toward refined and quantitative management [10].

For example, in the "Ecological Restoration Project for Permanent Excavated Slopes of a Hydropower Project on the Lancang River," designers and constructors carried out applications of solid waste-based revegetation substrates and the construction of digital slope surface monitoring systems. The project slope belongs to a strongly weathered rock slope. Traditional vegetation concrete consumes large amounts of cement, generates high carbon emissions, and suffers from frequent substrate cracking and peeling off in later periods. The technical team adopted fly ash from power plants and crushed engineering solid waste as substrate aggregates, and replaced part of the cement with biological binders to develop low-carbon revegetation spraying materials. After laboratory tests on substrate strength and water retention performance, the materials were applied to field construction. Soil moisture sensors, surface displacement sensors, and vegetation growth acquisition devices were deployed on slopes. Data were uploaded to cloud platforms in real time to track substrate integrity, rock-soil deformation, and vegetation growth. Operation and maintenance personnel identified potential slope surface hazards via monitoring data: refined water replenishing measures were adopted when substrate moisture was kept at low levels; on-site inspections were conducted immediately upon receipt of minor deformation signals. The project locally consumes engineering solid waste and cuts carbon emissions brought by raw material transportation. Digital monitoring replaces traditional regular manual inspections. In the project operation phase, low-carbon substrates maintain stable mechanical performance, and vegetation grows well. Integration of low-carbon ecological restoration materials and intelligent management and protection processes is realized.

5. Conclusion

To sum up, this paper mainly studies the ecological damage characteristics of excavated slopes in hydropower projects and mainstream ecological restoration technology types. It sorts out application conditions and engineering features of vegetation concrete slope protection, three-dimensional net grass planting, and lattice beam combined with revegetation composite restoration technologies, and summarizes three major application trends in the field of slope ecological restoration. Combined with typical engineering cases, it illustrates the concrete effects of collaborative safety governance, native vegetation community construction, as well as the integration of low-carbon materials and intelligent monitoring in slope governance. Research indicates that single protective measures cannot satisfy requirements for both slope stabilization and ecological reconstruction. Multi-technology coupling schemes are more suitable for complex slope environments of hydropower projects. Relevant analytical results can provide a theoretical basis and engineering references for scheme selection, engineering design, and on-site management of excavated slope restoration for hydropower projects in deep-cut gorge regions.

Disclosure statement

The authors declare no conflict of interest.

References

[1] He WB, 2025, Research on Water Resource Protection and Sustainable Development in Water Conservancy and Hydropower Projects. Guangxi Cyberspace Security and Informatization Federation. Proceedings of the 14th Academic Exchange Conference on Engineering Technology Management and Digital Transformation (Volume I), 569–571.

[2] Li WB, 2025, Ecological Quality Traceability and Standard Coordination: Research on Governance Paths for Environmental Problems During the Construction Period of Zala Hydropower Station in Xizang — Upholding Ecological Bottom Lines and Promoting Regional Brands. China Brand & Anti-Counterfeiting, 2025(17): 148–150.

[3] Li XX, Jiang DM, 2025, Exploration on System Operation Control Measures in Water Conservancy and Hydropower Projects Based on Risk-Oriented Thinking. Technical Supervision in Water Resources, 2025(12): 67–69 + 134.

[4] Wang M, 2025, Research on Impacts of Water Conservancy and Hydropower Projects on Aquatic Ecosystems and Mitigation Strategies. Maritime Safety, 2025(20): 85–87.

[5] Huang ZC, 2025, Analysis on Energy-Saving and Environment-Friendly Technologies in Water Conservancy and Hydropower Project Construction. Product Reliability Report, 2025(10): 114–116.

[6] Ji J, 2025, Exploration on Ecological Impact Assessment and Restoration Strategies in Water Conservancy and Hydropower Projects. Northeast Water Conservancy and Hydropower, 43(10): 31–33 + 59.

[7] Wang JX, Wang HC, 2025, Environmental Impact Assessment and Ecological Compensation Technologies in Water Conservancy and Hydropower Projects. Smart China, 2025(9): 76–77.

[8] Zhou LF, 2025, Water Resource Protection and Sustainable Utilization Based on Technologies of Quality Safety Technical Center for Water Conservancy and Hydropower Projects. Science and Technology & Innovation, 2025(17): 93–96.

[9] Ding JC, 2025, Impacts of Water Conservancy and Hydropower Projects on Regional River Ecological Environment. Global Logistics News, September 5, 2025, 3.

[10] Gu ZG, 2025, Research on Planning and Design of Water Conservancy and Hydropower Projects from the Perspective of Ecological Concepts. Maritime Safety, 2025(16): 67–69.

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