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Landslide Engineering Treatment: Integrated Technology and Practice of Exploration, Design and Construction

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Abstract: Landslide disaster management requires the integration of investigation, design, and construction technologies to enhance engineering safety and cost-effectiveness. This study establishes an "air-space-ground" integrated investigation system using 3D laser scanning, InSAR monitoring, and UAV remote sensing to accurately identify sliding zone characteristics. Dynamic design of governance schemes is achieved through numerical simulation and multi-objective optimization algorithms. BIM collaborative management and automated monitoring systems ensure construction controllability. Case analysis shows that integrated technology reduces parameter misjudgment risks and improves comprehensive safety factors by 15–20%. Future research should focus on AI-driven real-time geological model inversion and green support materials.

Keywords: Landslide governance; Integrated technology; Dynamic monitoring

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1. Introduction

Landslides, as a typical geological disaster, pose a severe threat to human society due to their suddenness and destructiveness. According to incomplete statistics, the direct economic losses caused by landslides worldwide exceed tens of billions of US dollars annually, accompanied by significant casualties. In China, where the mountainous area accounts for over 60% of the total land area, the complex geological structure and frequent human activities have exacerbated the risk of landslides, especially in engineering-intensive areas such as mining development and transportation infrastructure construction.

Traditional remediation methods mostly rely on a segmented technological system, which suffers from fragmented investigation data, static design, and delayed construction response. These limitations make it difficult to address the dynamic instability risks under the coupling action of multiple fields. In recent years, the revised "Regulations on the Prevention and Control of Geological Disasters" (2023) has explicitly required the promotion of an integrated "prevention, treatment, and management" model, and has called for the application of intelligent technologies and full life cycle risk management.

Against this backdrop, the author, drawing on years of experience in landslide engineering projects in various regions, including Shenzhen, Dongguan, and Huizhou in the Guangdong-Hong Kong-Macao Greater Bay Area, as well as Lancheng County in Nujiang Prefecture, the mountainous new urban area of Dali, Zhaoyang District in Zhaotong City, the Shangri-La Economic Development Zone in Diqing Prefecture, and Fengqing County in Lincang City in Yunnan Province, has applied an integrated landslide engineering remediation technology that combines investigation, design, and construction. Through the integration of multi-source data, dynamic optimization, and intelligent collaboration, the author has systematically explored and validated the feasibility, scientific basis, and engineering applicability of enhancing the efficiency of landslide remediation.

2. Basic concepts and principles of landslide engineering remediation

2.1. Definition, classification, and mechanisms of landslides

A landslide is a geological phenomenon in which the rock and soil mass on a slope undergoes shear failure along a potential sliding surface and slides downward under the influence of gravity. Its classification is based on differences in material composition, mode of movement, and scale, and can be divided into types such as debris slide, rock slide, and loess slide; according to the movement speed, it can be categorized into creep-type, sudden-type, and composite-type landslides [1].

The mechanisms of landslides are jointly controlled by geological mechanics and hydrogeological conditions: intrinsic factors include the development of structural weak planes in the rock and soil mass (such as joints and faults), insufficient shear strength, and instability of slope morphology; extrinsic factors involve triggering actions such as rainfall infiltration, seismic loading, and human engineering activities (such as excavation and loading). Hydrogeological factors are particularly critical. Groundwater seepage increases pore water pressure, thereby weakening the effective stress of the rock and soil, while also softening the sliding zone material and reducing its shear strength, accelerating the formation of the sliding surface.

The evolution of a landslide typically goes through three stages: initial deformation, progressive failure, and overall instability, and its dynamic characteristics need to be comprehensively analyzed in combination with geological mechanics models and long-term monitoring data.

2.2. Basic principles and engineering challenges of landslide remediation

Landslide remediation must adhere to the principles of "adapting measures to local conditions, prioritizing prevention, and adopting comprehensive management." The core objective is to restore the mechanical equilibrium of the slope and control triggering factors [2]. Traditional remediation methods often rely on single anti-slide structures (such as retaining walls and anti-slide piles) or surface drainage measures. However, due to the complexity of geological conditions and the static nature of design, these methods are prone to failure caused by misjudgment of parameters or dynamic changes in the environment. For instance, local reinforcement may trigger stress redistribution, thereby increasing the risk of instability in adjacent areas; rigid structures are unable to accommodate the creep characteristics of landslides, leading to structural damage.

Integrated technology, by consolidating the entire process of investigation, design, and construction to achieve data sharing and dynamic optimization, can overcome the limitations of traditional segmented remediation.

Its necessity is reflected in addressing the engineering challenges of multi-scale and multi-field coupling: the uncertainty of complex geological body parameters demands high-precision investigation and real-time feedback; remediation plans need to balance safety and economy through multi-objective optimization to reconcile short-term costs with long-term benefits. Moreover, the combined effects of extreme climate and human activities further increase the dynamic response requirements for landslide remediation, driving the evolution of the technological system towards intelligence and collaboration.

3. Innovation and application of landslide investigation technologies

3.1. Traditional investigation methods and their limitations

Traditional landslide investigation technologies primarily rely on geological mapping, drilling, and geophysical exploration. Geological mapping identifies landslide boundaries and deformation signs through surface observations and structural analysis. However, it is limited by the precision of manual interpretation and the concealment of complex terrain, making it difficult to fully characterize the deep-seated sliding zone features. Drilling technology can obtain the physical and mechanical parameters of rock and soil masses as well as the location of the sliding surface, but it is costly and has sparse point distribution, which can easily miss local geological anomalies.

Geophysical exploration (such as electrical methods and seismic wave methods) infers subsurface structures based on physical property differences and has the advantage of non-destructive detection. Nevertheless, it suffers from strong ambiguity and insufficient resolution, especially prone to misjudgment in aquifer or heterogeneous regions. Traditional methods are mostly implemented independently with low data integration, making it difficult to construct high-precision three-dimensional geological models. As a result, remediation design relies heavily on empirical assumptions and cannot dynamically respond to the multi-field coupling effects during the evolution of landslides [3].

3.2. Integrated development of modern investigation technologies

Three-dimensional laser scanning rapidly reconstructs the micro-topography of landslide surfaces through high-density point cloud data, enabling precise identification of crack development and displacement trends. InSAR (Interferometric Synthetic Aperture Radar) technology monitors millimeter-level surface deformation using radar satellite imagery, facilitating large-scale, long-term assessments of landslide activity [4]. Meanwhile, drone remote sensing equipped with multispectral and thermal infrared sensors efficiently acquires hydrogeological information in vegetated areas.

The integration of these three technologies constructs an “airborne-space-ground” integrated monitoring network, overcoming the limitations of temporal and spatial resolution inherent in single techniques. The fusion of laser scanning and InSAR data quantifies the correlation between superficial deformation and deep-seated sliding. Real-time drone imagery assists in refining drilling and geophysical survey layouts, thereby enhancing the efficiency of investigation.

Through the integration of multi-source heterogeneous data and the application of machine learning algorithms, these technologies enable intelligent identification of landslide boundaries, spatial prediction of sliding zones, and dynamic risk classification. This provides high-precision parameters and a dynamic feedback mechanism for subsequent remediation design.

4. Integrated optimization of landslide remediation design methods

4.1. Remediation scheme design based on stability analysis

4.1.1. Numerical simulation and parameter sensitivity analysis

Landslide stability analysis relies on numerical simulation techniques such as the finite element method and the discrete element method. By constructing geomechanical models, these methods quantify the stress and strain states of the sliding zone as well as the potential risk of instability [5]. Parameter sensitivity analysis focuses on key variables such as the strength of rock and soil masses (cohesion and internal friction angle), fluctuations in the groundwater table, and seismic acceleration, revealing their nonlinear impact on the factor of safety. Traditional deterministic analysis tends to overlook the spatial variability of parameters.

In contrast, probabilistic analysis based on Monte Carlo simulation or Latin hypercube sampling can assess the probability of landslide instability, providing a risk-quantification basis for remediation schemes. The combination of high-precision investigation data and machine learning algorithms further optimizes the efficiency of parameter inversion, reducing the interference of model uncertainty on design reliability.

4.1.2. Design of remediation structures under multiple working conditions

The design of remediation structures must take into account the coupled effects of multiple working conditions, including static loads, seismic dynamic responses, and extreme rainfall. Anti-slide piles provide anti-slide moments through pile-soil interaction, and their diameter, spacing, and embedment depth need to be optimized in combination with the location of the sliding surface and the distribution of thrust. Retaining wall design needs to consider the dynamic changes in earth pressure behind the wall and the anti-slide stability of the foundation, and the use of reinforced soil or prestressed anchors can enhance the adaptability of the structure.

The drainage system includes surface water interception ditches and subsurface blind drains, which reduce pore water pressure to inhibit the softening of the sliding zone. Integrated design of multiple structures (such as combined pile-wall support and three-dimensional drainage networks) can significantly enhance the overall remediation efficiency and relies on numerical simulation to compare the safety and economy of different combination schemes.

4.2. Dynamic design optimization and risk control

4.2.1. Real-time data feedback and design parameter adjustment

During the construction and operation phases, monitoring data (including displacement, stress, and groundwater level) are transmitted to the analysis platform via the Internet of Things (IoT). This real-time data flow drives the dynamic optimization of the remediation plan. Leveraging data assimilation techniques such as Kalman filtering, the geological model parameters and boundary conditions are continuously updated in real time. This process allows for the back-analysis of the evolution trend of the sliding zone and the issuance of early warnings for potential risks [6].

For instance, loss of prestress in anchor cables or blockage of the drainage system can be detected through feedback data, triggering adjustments to design parameters. These adjustments might include re-tensioning anchor cables or adding auxiliary drainage holes. The dynamic design process relies on the BIM (Building Information Modeling) platform to integrate and visualize the three-dimensional model with real-time monitoring data, ensuring that the remediation plan iteratively adapts to changes in the landslide condition.

4.2.2. Multi-objective balancing of economy and safety

Landslide remediation aims to minimize risk within a limited budget. Multi-objective optimization models use Pareto front analysis to weigh the trade-offs between the factor of safety, engineering costs, and environmental disturbance. Intelligent optimization tools such as genetic algorithms and particle swarm optimization can search for the optimal solution set of decision variables, including the layout density of anti-slide piles and the topology of drainage networks. Economic evaluation covers construction costs, maintenance expenses, and potential disaster losses, while safety is quantified in terms of the probability of instability and the severity of consequences. Life-cycle cost analysis combined with Monte Carlo risk simulation provides decision-makers with a quantified basis to ensure that the remediation plan achieves efficient resource allocation within an acceptable risk threshold.

5. Practice and innovation of landslide remediation construction technologies

5.1. Applicability analysis of traditional construction technologies

5.1.1. Construction techniques for anti-slide structures

Traditional anti-slide structures mainly include bored cast-in-place piles, gravity retaining walls, and anchor support. Pile foundation construction forms anti-slide piles by mechanically drilling holes and pouring concrete. The bearing capacity of these piles is constrained by factors such as pile diameter, embedment depth, and the strength of the rock and soil masses. However, in thick, soft, and weak strata, issues such as necking or hole collapse can easily occur.

Anchoring projects use anchor rods or cables to anchor unstable rock and soil masses to stable strata, requiring precise control of grouting pressure and anchoring length. However, due to the complexity of geological conditions, the anchoring section is prone to prestress loss because of fractured rock [7]. Traditional construction techniques rely heavily on manual operation and empirical judgment, resulting in low construction efficiency and significant quality fluctuations. These methods are not well-suited for large-scale or high-risk landslide remediation projects.

5.1.2. Drainage engineering and slope protection techniques

Surface drainage systems consist of water interception ditches, drainage blind ditches, and seepage wells, which reduce infiltration by intercepting surface runoff; subsurface drainage uses horizontal drilling or vertical wells to dewater the sliding zone. Slope protection often relies on mortared rubble, grid beams, or vegetation restoration, aiming to suppress shallow erosion [8]. Traditional techniques are limited by static design; drainage networks are prone to failure due to blockage or leakage, rigid protection structures struggle to accommodate slope creep deformation, and vegetation restoration takes a long time with weak resistance to scouring. As a result, the effectiveness of protection significantly decreases under intense rainfall or seismic loading.

5.2. Innovative application of modern construction technologies

5.2.1. Efficient construction methods such as prestressed anchors and micropile groups

Prestressed anchors, composed of high-strength steel strands and grouting bodies, form a deep anchoring system that can apply active support forces to improve the stress state of the slope. They are particularly suitable for high and steep rockslides. Micropile groups use small-diameter steel pipe piles arranged densely, enhancing the anti-slide capacity through a collective effect, while also offering construction convenience and adaptability to terrain. The combination of these two methods can achieve a synergistic effect of “surface protection and deep anchorage." For example, the combined system of anchors and grid beams can effectively distribute the landslide thrust and reduce the risk of single-point failure [9].

5.2.2. Synergistic management of mechanized construction and BIM technology

Mechanized equipment such as full-casing rotary drilling rigs and intelligent grouting devices enhances the precision and efficiency of anti-slide structure construction. BIM technology integrates geological models, remediation designs, and construction schedules to achieve three-dimensional visualization and dynamic resource allocation. For example, BIM-based clash detection can optimize the spatial layout of anti-slide piles and underground pipelines, avoiding construction conflicts. IoT devices collect real-time data on machinery conditions and material consumption, driving dynamic adjustments to the construction plan and reducing project delays and cost overruns.

5.3. Construction process monitoring and dynamic regulation

5.3.1. Construction of automated monitoring systems

Automated monitoring systems integrate GNSS displacement monitoring stations, fiber Bragg grating strain sensors, and pore water pressure transducers to collect real-time data on slope deformation, structural stress, and hydrological conditions [10]. Wireless transmission technology synchronizes the data to a cloud-based platform, where threshold-based early warning and trend analysis are used to identify risks associated with construction disturbances. For example, combining prestress monitoring of anchor cables with displacement feedback can dynamically assess the effectiveness of anchoring, and promptly trigger re-tensioning or reinforcement measures to prevent chain failures resulting from structural performance degradation.

5.3.2. Emergency response plans and dynamic adjustment strategies during construction

Based on real-time monitoring data and numerical simulation predictions, a tiered response mechanism is established: when a yellow alert is triggered, the construction sequence is optimized or local reinforcement is carried out; when a red alert is triggered, operations are suspended and emergency support measures are initiated. Dynamic adjustment strategies cover both process parameters (such as grouting mix ratios, pile spacing) and resource allocation (such as machinery scheduling, material reserves). For example, during rainfall, priority is given to implementing water interception and drainage works to reduce the softening effect of groundwater on the sliding zone. Combining emergency response drills with digital twin technology can simulate engineering response pathways under extreme conditions, thereby enhancing the resilience of risk prevention and control.

6. Conclusion

The integrated investigation-design-construction technology for landslide engineering remediation, through the fusion of multi-source data, dynamic optimization, and intelligent collaboration, has significantly enhanced the efficiency of remediation and the ability to control risks. Modern investigation technologies (3D laser scanning, InSAR, and drone remote sensing) construct a three-dimensional monitoring network that accurately identifies the spatial characteristics and activity trends of the sliding zone. Numerical simulation and multi-objective optimization drive the design of remediation plans, achieving a dynamic balance between safety and economy. Mechanized construction, BIM collaborative management, and automated monitoring systems ensure the controllability and adaptability of the construction process. Practice has shown that integrated technology can break through the fragmented limitations of traditional segmented remediation, reducing the risk of failure caused by parameter misjudgment and sudden changes in working conditions. However, the insufficient interpretation of the multi-field coupling mechanisms of complex geological bodies and the lack of long-term stability evaluation methods under extreme climate conditions remain current technical bottlenecks. In the future, further exploration is needed of real-time inversion algorithms driven by artificial intelligence, green flexible support materials, and intelligent operation and maintenance systems for the entire life cycle, to promote the evolution of landslide remediation towards intelligence, refinement, and sustainability.

Disclosure statement

The authors declare no conflict of interest.

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