Comprehensive Research on Design and Calculation for Slope Treatment Engineering in the Ecological Restoration Construction Project of Abandoned Mine Sand Hills in Huitong County (EPC)

Kailin Li[1], Jinglong Mo[2], Yongqi Zhang[3], Weijian Zhou[3,4,*], Jing Guo[4]

1 Hunan Jianghui Engineering Technology Co., Ltd, Changsha, Hunan 410000, China

2 Hunan University of Finance and Economics Postal, Changsha, Hunan 410000, China

3 Hunan Vocational College of Engineering, Changsha, Hunan 410151, China

4 Xishi Ecological Doctoral Innovation Station, Yiyang, Hunan 413000, China

Corresponding Author: Weijian Zhou (476341099@qq.com)

Abstract: This study, based on the background of the ecological restoration construction project of abandoned mine sand hills in Huitong County, systematically analyzes the design theory and engineering practice of comprehensive slope treatment under complex geological conditions. Focusing on four typical unstable slopes within the area, it integrates principles from geotechnical engineering, hydrogeology, and ecological restoration to construct a combined reinforcement system. This system centers on anchor rod (cable) lattice beams, anti-slide piles, and gravity retaining walls, supplemented by systematic drainage. Through a combination of the limit equilibrium method and numerical simulation, the design parameters, mechanical mechanisms, and collaborative working performance of each support structure are detailedly demonstrated. Calculation results indicate that the adopted design methodology can significantly enhance the slope stability safety factor, meeting long-term service requirements. This paper further explores the integration pathways of ecological slope protection technology and intelligent monitoring concepts in modern slope engineering, aiming to provide theoretical reference and engineering paradigms for the treatment of geological environments and ecological restoration in similar mining areas.

Keywords: Slope Treatment; Combined Support System; Stability Analysis; Ecological Restoration; Design Theory; Mining Environment

1. Introduction

Mountainous towns and concentrated mining areas in China commonly face slope instability problems induced by engineering activities and natural weathering. Their treatment is crucial for safeguarding people's lives and property and ensuring the sustainable development of the ecological environment. The geological conditions within Huitong County, Hunan Province, are complex, with frequent heavy rainfall. Disaster risks associated with historically legacy mining slopes and natural slopes are prominent. The four slope treatment projects focused on in this study integrate structural reinforcement and ecological restoration, serving as typical cases for exploring the "engineering-ecology" collaborative treatment model, holding significant value for enriching the theory of slope hazard prevention and control. In recent years, research in the field of slope engineering has developed from stability analysis towards multi-field coupling, ecological synergy, and intelligent monitoring. In terms of support theory, the collaborative working mechanism of anchor rods (cables) and lattice beams [1], and the reinforcing effect of vegetation roots on shallow soil [2] have been thoroughly investigated. At the technical application level, real-time monitoring systems based on the Internet of Things [3] and BIM-based whole-life-cycle management [4] are being gradually promoted. These advancements provide solid theoretical and technical support for the design optimization and effect evaluation of this study.

2. Engineering Geological Conditions and Stability Assessment

The slopes in the treatment area are primarily composed of Quaternary silty clay and Proterozoic sandy slate. The rock mass is strongly weathered due to tectonic influence, with well-developed joints and fissures. The geometric characteristics of each slope and the main physical and mechanical parameters of the rock and soil masses are presented in Tables 1 and 2. Historical disasters indicate that slope instability mostly occurs during periods of continuous heavy rainfall, belonging to the typical rainfall-induced landslide type.

Table 1: Basic Characteristics of Slopes for Treatment.

Slope Name	Length (m)	Slope Height (m)	Main Rock/Soil Layers	Initial Stability State
Paotuan Township	140	25-49	Silty clay, Strongly weathered slate	Unstable
Changzhai School	70	30-50	Silty clay, Strongly-Moderately weathered slate	Marginally Stable
Mingde School	49-81	5-30	Soil-rock mixed slope	Unstable
Jinziyan Township	43-120	2-15	Strongly weathered slate, Soil slope	Marginally Stable

Table 2: Design Values of Rock and Soil Mass Mechanical Parameters.

Stratum	Natural Unit Weight (kN/m³)	Cohesion c (kPa)	Internal Friction Angle φ (°)	Bearing Capacity (kPa)
Silty Clay	18.2-19.3	18-22	14-19	180
Strongly Weathered Sandy Slate	23.1-24.0	35-45	25-33	270-360
Moderately Weathered Sandy Slate	24.1-25.0	50	30-38	1500-1800

3. Design Theory and Calculation Methods

3.1 Slope Stability Analysis Methods

This project employs the Limit Equilibrium Method (LEM) for overall stability evaluation, combined with the Strength Reduction Method (SRM) for local verification. The calculation software used is Lizheng Geotechnical 7.0 (Beijing), widely applied in domestic slope engineering. Its core algorithm is based on the Morgenstern-Price method, suitable for heterogeneous slopes with multiple potential slip surfaces [5-7].

3.2 Design Principles and Safety Standards

The design follows the principles of "strengthening the toe and middle section, drainage first, and comprehensive treatment". According to the Technical Code for Building Slope Engineering (GB50330-2013) [8], the safety grades for the Paotuan Township, Changzhai School, and Mingde School slopes are designated as Grade I, with a design safety factor of 1.35. The Jinziyan Township Government slope is designated as Grade II, with a safety factor of 1.30.

3.3 Design of Anchor Rod (Cable) Support System

Anchor rods, serving as the main anti-sliding components, have their optimal downward inclination angles determined by integrating theoretical calculation and engineering experience. The design anchoring force per rod Pt is obtained from the distribution of landslide thrust, based on which the rod cross-sectional area Ag and anchorage length la are checked:

$$A_g = \frac{k_a \cdot P_t}{f_y}, \quad l_a = \frac{k_a \cdot P_t}{\pi D f_{rbk}}$$

In the formula, ka is the safety factor, f_y is the tensile strength of the steel, and f_{rbk} is the characteristic value of the bond strength between the grout and the rock/soil mass. The design fully considers group anchor effects and deformation coordination of prestressed anchor cables.

3.4 Internal Force Analysis and Design of Lattice Beams

The lattice beam system is simplified using the Winkler elastic foundation beam model. Anchor rod tension forces are converted into nodal loads, distributed according to the stiffness ratio of longitudinal and transverse beams. The "inverted beam method" is employed to calculate the internal forces (bending moment and shear force) of the beams. Reinforcement design strictly adheres to the Code for Design of Concrete Structures (GB50010-2010), ensuring flexural capacity of the normal section and shear capacity of the inclined section.

3.5 Design of Anti-Slide Piles and Retaining Walls

The Mingde School slope with high thrust, anti-slide pile support is adopted. Pile internal forces are calculated using the "K method", considering the combined action of landslide thrust and foundation reaction. Gravity retaining walls are mainly subjected to checks against sliding, overturning, and foundation bearing capacity to ensure stability under various load combinations.

3.6 Hydraulic Design of Drainage System

The surface drainage system is key to the long-term stability of the slope. Design runoff is calculated using the rational formula method, and the flow capacity of the channels is checked using Manning's formula. The maximum flow velocity in open drainage ditches is controlled within 4 m/s, with a 0.2m freeboard set to ensure safe operation under a 50-year return period storm intensity.

4. Implementation of Treatment Schemes and Verification of Calculation Results

4.1 Anchor Rod Lattice Beam System

A support system consisting of fully grouted anchor rods (length 9m, Φ28) and C30 concrete lattice beams with a 300mm×300mm cross-section was adopted. Calculations show that the post-treatment slope safety factor increased to 1.52. The maximum bending moment in the lattice beam at the nodes was 85 kN·m, which can be satisfied by providing 4Φ18 longitudinal reinforcement bars.

4.2 Composite System of Anchor Rods and Anchor Cables

This slope employed a combined scheme of anchor rods (6-12m) and prestressed anchor cables (12-16.5m). The lattice beam cross-section was increased to 400mm×400mm to withstand greater anchoring forces. Stability analysis indicates that the composite support effectively controlled both deep and shallow sliding, meeting the safety factor requirement for Grade I slopes.

4.3 Differentiated Comprehensive Treatment

In response to the characteristics of multiple sections and various types of hazards, a "section-by-section treatment" strategy was implemented: anchor rod lattice beams were used for the high-steep rock sections (A-B); anti-slide piles with connecting beams were used for sections with thick soil and high thrust (C-D); and gravity retaining walls were used for medium-low height fill sections. This differentiated design reflects the optimization concept based on a precise geological model.

4.4 Reinforcement Scheme Dominated by Anchor Cables

This slope primarily utilized long anchor cables (12-16.5m) as the main load-bearing components, combined with 450mm×450mm lattice beams to form a strong support system. Calculation verification showed that the design cable tension was 455 kN, with an anchorage length of 8 m, achieving a safety factor of 1.65, effectively ensuring the safety of the road at the slope toe.

5. Discussion

5.1 Integration and Application of Ecological Restoration Technology

Traditional lattice beams in this design reserved spaces for vegetation growth, creating conditions for later hydroseeding and vegetation recovery. Research indicates that plant roots can enhance the shear strength and erosion resistance of surface soil, complementing the engineering structures. Future designs could more proactively consider the mechanical contribution of ecological materials.

5.2 Prospects for Intelligent Construction and Long-Term Monitoring

Although the design of this study is based on detailed investigation and theoretical calculations, dynamic feedback during construction and long-term post-construction monitoring are crucial. It is recommended to introduce distributed optical fiber sensing technology to real-time monitor anchor stress and slope deformation, combined with numerical models for prediction and early warning, achieving intelligent management of slope operation and maintenance.

5.3 Potential of Numerical Simulation in Optimizing Design

This study primarily relied on the limit equilibrium method. In the future, numerical simulation software such as FLAC3D or PLAXIS could be further utilized to simulate the entire process of excavation unloading and support installation, allowing for more refined analysis of the stress-strain field, thereby optimizing support parameters and achieving dynamic design.

6. Conclusion

For the four slopes with varying geological conditions in Huitong County, the comprehensive treatment scheme adopted in this research—combining anchor rod (cable) lattice beams, anti-slide piles, retaining walls, and systematic drainage—is reasonable and effective. Both theoretical calculations and software verification indicate that the post-treatment slope stability safety factors are significantly improved, meeting code requirements.

The design integrates limit equilibrium theory, the elastic foundation beam model, and hydraulic calculations. Parameter selection is well-founded, and calculation methods are rigorous, reflecting the development trend of modern geotechnical engineering design from qualitative to quantitative and from single to systematic.

Engineering practice demonstrates that combining structural reinforcement with ecological restoration, and planning for intelligent monitoring interfaces prospectively, is an inevitable direction for enhancing the whole-life-cycle performance of slope engineering and achieving sustainable development. This study provides a referable technical pathway and theoretical reference for ecological restoration and geological hazard treatment in similar mining areas.

Funding

A Project Supported by Hunan Province Vocational College Education and Teaching Reform Research Project (ZJGB2023323), and funded by School-level project of Hunan Vocational College of Engineering (GC23ZXKT03), and Scientific Research Projects for College Students of Hunan Vocational College of Engineering (GCDXS2510).

Acknowledgements

Thank you to the scholars and their viewpoints involved in this paper for their inspiration, and thank you to Du Yajun for his guidance and revision suggestions. Thank you to Professor Liu Chunming for his guidance on field geological work and valuable suggestions on paper writing.

References

[1] Liu Bo, Li Ning, Zhao Xiaoyan. Study on group anchor effect in stability analysis of anchor-supported slopes. Rock and Soil Mechanics, 2020, 41(5): 1623-1632.

[2] Wang Wei, Zhang Jianguo, Liu Xiaoming. Experimental study on synergistic slope stabilization mechanism of vegetation roots and lattice beams. Chinese Journal of Rock Mechanics and Engineering, 2021, 40(3): 527-536.

[3] Li Zhijun, Wu Shunchuan, Zhou Guoqing. Development and application of an IoT-based intelligent slope monitoring system. Journal of Engineering Geology, 2022, 30(2): 456-465.

[4] Chen Hong, Yang Guanghua, Xu Guangming. Application of BIM technology in slope engineering design and construction management. Journal of Civil Engineering and Management, 2023, 40(1): 89-97.

[5] Zheng Yingren, Chen Zuyu, Wang Gongxian, et al. Slope and Landslide Engineering Treatment (Second Edition) . Beijing: China Communications Press, 2018.

[6] Li, X., Wang, Y., & Zhang, L. (2021). Real-time monitoring of anchor stress in slope engineering using distributed optical fiber sensing. Engineering Geology, 291, 106234.

[7] Zhang, H., & Wang, J. (2022). Ecological reinforcement of slopes with vegetation and structural systems: A review. Journal of Cleaner Production, 330, 129876.

[8] GB50330-2013, Technical Code for Building Slope Engineering. Beijing: China Architecture & Building Press, 2013.