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Comprehensive Evaluation and Integrated Treatment Research on Slope Stability Based on Multi-Method Coupling for the Bamboo Industrial Park in Huitong County

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

[1] Hunan University of Finance and Economics Postal, Changsha, Hunan 410000, China

[2] Huitong Branch of Hunan Construction Engineering Survey Institute Co., Ltd, Huaihua, Hunan 418300, 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 addresses the stability and treatment issues of high-steep mixed slopes at the Bamboo Industrial Park in Huitong County, employing a multi-method coupling analysis combining the Limit Equilibrium Method (Bishop's method) and the Stereographic Projection Method. Quantitative calculations indicate that the slopes are in a marginally stable to basically stable state under natural conditions (Fs=0.986-1.214), but become unstable under saturated conditions (Fs=0.743-0.903), revealing that rainfall infiltration is the dominant triggering factor. Stereographic projection analysis further identifies multiple sets of unfavorable structural planes in the rock slopes, which are prone to wedge-shaped collapses and planar sliding. Based on this, a differentiated "zoned and classified" comprehensive treatment strategy is proposed, constructing an integrated technical system of "support and reinforcement - three-dimensional drainage - ecological restoration - full-cycle monitoring". This provides a complete solution from accurate evaluation to safe treatment for similar complex slope engineering projects.

Keywords: Slope engineering; Stability evaluation; Circular sliding method; Stereographic projection; Structural plane analysis; Comprehensive treatment; Monitoring and early warning

1. Introduction

Engineering construction in China's mountainous and hilly regions often results in a large number of artificial slopes, the stability of which is directly related to engineering safety and public safety. The slope engineering at the Huitong County Bamboo Industrial Park has formed a group of high-steep mixed slopes with heights of 8-17 meters and a total length of nearly 770 meters after site levelling. Adjacent to factories, roads, and high-voltage lines, these slopes belong to the first safety grade, making stability issues extremely prominent.

Current slope stability analysis is developing towards a comprehensive direction combining qualitative evaluation and quantitative calculation. A single method often struggles to fully reveal the failure mechanism of complex slopes. Based on detailed geological investigation, this study innovatively couples the Limit Equilibrium Method (quantitative) and the Stereographic Projection Method (qualitative) for systematic evaluation of soil, soil-rock, and rock slopes. It aims to precisely determine slope stability states and potential failure modes through multi-dimensional analysis, and accordingly propose economically reliable dynamic design and comprehensive treatment plans, providing a scientific paradigm and technical support for the engineering practice of high-risk mixed slopes.

2. Engineering Geological Conditions

2.1 Regional Geology and Topography

The proposed site is located within an area influenced by the Neocathaysian tectonic system, belonging to an erosional-structural hilly landform. The original terrain had significant relief. After artificial excavation and backfilling modification, a stepped topography higher in the south and lower in the north, higher in the east and lower in the west, was formed. Site levelling will create two main slope sections, A and B. The slope orientations vary, with slope heights of 8-17m and slope angles of 35°-80°, locally near-vertical. The topographic conditions are extremely unfavorable for slope stability.

2.2 Stratigraphy and Lithology and Their Engineering Properties

Based on drilling data, the site strata from top to bottom are as follows:

Miscellaneous Fill (Layer ①): Variegated color, loose to slightly dense, mainly composed of slate fragments/boulders and cohesive soil, with a short filling age (1-3 years) and incomplete self-weight consolidation. This layer exhibits significant thickness variation (0.20-18.60m), has a loose structure, low strength, high compressibility, and relatively good permeability. It is a weak layer for slope instability.

Silty Clay (Layer ②): Yellow-brown, plastic, a residual product of slate. This layer is prone to softening and disintegration when wet, leading to a sharp decrease in shear strength, posing a potential threat to slope stability.

Highly Weathered Slate (Layer $③_1$): Brown-yellow to brown, granular structure, extremely fragmented rock mass, very soft rock quality, basic quality grade V. This layer has poor mechanical properties and is susceptible to further weathering, representing a potential sliding zone.

Moderately Weathered Slate (Layer $③_2$): Gray-yellow to bluish-gray, medium-thick bedded, blocky structure, relatively developed joints and fissures, soft rock quality, relatively complete to complete rock mass, basic quality grade IV. This layer is a good foundation bearing layer, but the development of its structural planes controls the stability of rock slopes.

2.3 Hydrogeological Conditions

The site is poor in groundwater, mainly consisting of perched water stored in the miscellaneous fill, recharged by atmospheric precipitation, with large dynamic variations. The miscellaneous fill layer is a weak to medium permeability layer, the silty clay layer is a relatively impermeable layer, and the highly weathered slate is a weak permeability layer. During the rainy season, a large amount of surface water infiltrates along the loose fill and bedrock fissures. This increases the weight of the slope mass on one hand, and softens the rock and soil mass while generating dynamic water pressure on the other, constituting the primary external cause for inducing slope instability.

2.4 Seismic Effects

The seismic fortification intensity of the site is 6 degrees, with a design basic seismic acceleration value of 0.05g, and the design earthquake group is the first group. Although seismic action itself is not a controlling condition, areas located on slopes and with locally thick fill (such as near ZK91 in Zone B) belong to seismic unfavorable sites for buildings and should be considered in the design of support structures.

3 Multi-Method Coupling Analysis of Slope Stability

3.1 Quantitative Stability Calculation for Soil and Soil-Rock Slopes (Limit Equilibrium Method)

3.1.1 Calculation Model and Parameters

Three representative profiles—25-25′ (soil-rock slope in Zone A), 32-32′ (soil slope in Zone A), and 41-41′ (soil slope in Zone B)—were selected as calculation objects. The Bishop's circular sliding method in the Lizheng Geotechnical 7.0 software was used for automatic searching of the most critical slip surface.

Calculation Conditions: Two most unfavorable conditions were considered, Natural Condition (self-weight) and Saturated Condition (self-weight + heavy rain). The seismic condition was not considered a controlling condition due to low intensity.

Geotechnical Parameters: Determined comprehensively based on indoor soil tests, in-situ test results, and regional experience, see Table 1. Saturated condition parameters considered the effects of increased unit weight and strength softening due to rainwater infiltration.

Safety Factor Standard: The safety grade for this slope engineering is Level 1, and it is a permanent slope. Referring to the "Technical Code for Building Slope Engineering" (GB50330-2013), the corresponding slope stability safety factor calculated by the circular slip surface method should not be less than 1.35.

Table 1: Adopted Values of Physical and Mechanical Parameters for Slope Stability Calculation.

Rock/Soil Name	State	Unit Weight γ (kN/m^3)	Cohesion c (kPa)	Internal Friction Angle φ (°)
Miscellaneous Fill①	Natural	18.0	15.0	10.0
	Saturated	18.3	10.0	8.0
Silty Clay②	Natural	19.5	26.1	14.5
	Saturated	19.7	20.0	12.0
Highly Weathered Slate③$_1$	Natural/ Saturated	23.0	55.0	22.0

3.1.2 Calculation Results and Analysis

The stability calculation results for each profile under different conditions are summarized in Table 2.

Result Analysis: ① Significant Impact of Condition Contrast: The safety factors for all profiles under saturated conditions decreased substantially compared to natural conditions (by 20%-35%) and all fell below the critical stability value of 1.0. This fully verifies the rule that "water is the great enemy of slope engineering," confirming that heavy rain is the primary trigger for slope instability in this project. ② The soil-rock slope in Zone A (25-25′) is relatively better under natural conditions, approaching the stability standard for temporary slopes. This is related to the presence of a highly weathered rock layer with relatively better engineering properties at its lower part. In contrast, the pure soil slopes in Zones A and B (32-32′, 41-41′) are already in a marginally unstable state under natural conditions, reflecting the extremely poor self-stability of

recently placed fill. ③ Comparing calculation results for the current state and the post-leveling design state (e.g., Profile 32-32′), the increased slope height after excavation further reduces the safety factor. This indicates that engineering activities have altered the original stress field and exacerbated slope instability. "Support before excavation" or "excavate and support simultaneously" (top-down construction method) must be adopted during construction.

Table 2: Slope Stability Calculation Results for Typical Profiles.

Profile Number	Represented Zone and Type	Calculation Condition	Minimum Safety Factor Fs	Stability State Evaluation	Characteristics of slope Slip Surface Location
25-25′	Rock slope in Zone A	Natural	1.206	Basically stable	Cross the plain fill and cut the foot of the slope.
		Saturated	0.899	Unstable	Same as the natural condition, the sliding arc deepens.
32-32′	Soil slope in Zone A	Natural	0.986	under stability	It mainly slides along the internal circular arc of the plain fill.
		Saturated	0.756	Unstable	The sliding arc range is expanded, and the safety factor is significantly reduced.
41-41′	Soil slope in Zone B	Natural	1.008	under stability	Sliding along the interior of the fill, the trailing edge near the top of the slope.
		Saturated	0.743	Unstable	Sliding range and sliding force increased significantly.

3.2 Qualitative Stability Analysis for Rock Slopes (Stereographic Projection Method)

For the rock slope sections involved in Zones A and B, their stability is mainly controlled by the combination relationships of rock mass structural planes (joints, fissures,

bedding planes). Qualitative analysis using the Stereographic Projection Method can intuitively judge the spatial geometric relationship between structural planes and the slope face, predicting potential failure modes.

3.2.1 Analysis Principle and Method

Stereographic projection is a graphical method that projects surfaces and lines in three-dimensional space onto a two-dimensional horizontal circle. By drawing the projection great circles of the slope face, slope crest surface, and various groups of structural planes, the following can be analyzed:

1) The relationship between the dip direction of structural planes (or their intersection lines) and the dip direction of the slope face.

2) The relationship between the dip angle of structural planes (or intersection lines) and the slope angle.

3) Based on the above relationships, judge whether the slope belongs to a stable, basically stable, or unstable structure, and preliminarily determine the failure mode (e.g., planar sliding, wedge sliding, toppling failure).

3.2.2 Stereographic Projection Analysis for Zone A Rock Slope

Slope Characteristics: Rock slope section on the north side of Zone A, slope dip direction 0° (due north), slope angle 55°-75°, locally >80°. Field mapping identified four main joint sets:

Joint Set ①: Attitude 105°∠52-56° (dipping SE, steep dip angle);

Joint Set ②: Attitude 30°∠57-65° (dipping NE, steep dip angle);

Joint Set ③: Attitude 235°∠65-70° (dipping SW, very steep dip angle);

Joint Set ④: Attitude 55°∠35-42° (dipping ENE, moderate dip angle).

Stereographic Projection Analysis (refer to Figures1, 2). Plotting the above structural planes and the slope face (0°/75°) on the same stereographic net shows:

The dip directions of Joint Set ② (30°∠57-65°) and Joint Set ④ (55°∠35-42°) have small angles (30°-55°) with the slope dip direction (0°), belonging to "dip slope" or "oblique dip slope" structural planes.

The dip angle of Joint Set ② (57-65°) is less than the slope angle (75°). Its intersection line with other sets outcrops on the slope face, and the plunge of the intersection line is less than the slope angle but greater than the rock mass friction angle, meeting the conditions for wedge sliding.

The dip angle of Joint Set ④ is relatively gentle (35-42). Although less than the slope angle, its combination with the slope face alone easily forms unstable blocks.

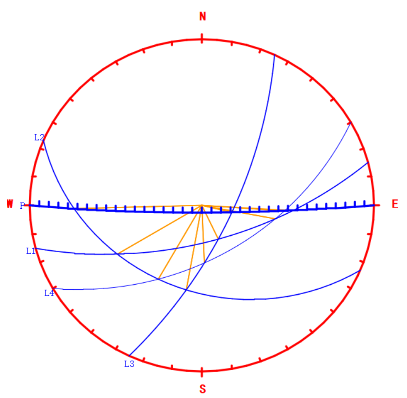

Figure 1: The Stereographic Projection Analysis Diagram of Rock Mass Structural Plane Of Rock Slope After Excavation in Zone A

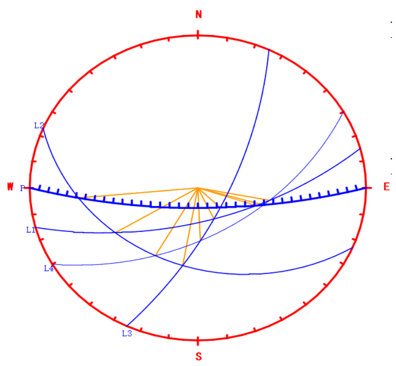

Figure 2: The Stereographic Projection Analysis Diagram of Rock Mass Structural Plane of Rock Slope After Excavation in Zone A

The rock slope in Zone A belongs to an unstable structure. The main failure modes are wedge-shaped collapse or sliding formed by the combination of Joint Sets ②, ④, and other joint sets (such as ① or ③). There is also a risk of planar sliding along Joint Set ④. After slope excavation, the formation of free faces makes local rock block collapse and spalling highly likely.

3.2.3 Stereographic Projection Analysis for Zone B Rock Slope

Rock slope section on the west side of Zone B, slope dip direction 90° (due east), slope angle 40°-60°.Multiple joint sets similar to Zone A are developed. Stereographic Projection Analysis (refer to Figure 3): Plotting the main structural planes and the slope face (90°/50°) for analysis shows:

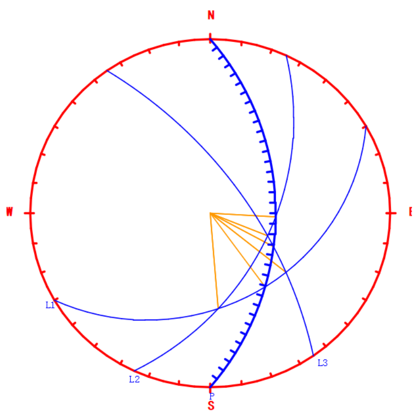

Figure 3: The Stereographic Projection Analysis Diagram of Rock Mass Structural Plane of Rock Slope After Excavation in Zone B.

Joint Set ① (105°∠ 52-56°) dips obliquely to the slope face (90°) with an angle of 15°, and its dip angle is greater than the slope angle, indicating a relatively lower degree of disadvantage.

The dip directions of Joint Set ② (30°∠57-65°) and Joint Set ④ (55°∠35-42°) are nearly opposite or intersect the slope dip direction at a large angle, which is unfavorable for downslope sliding.

However, attention should be paid to the possible existence of other gently dipping structural planes, not yet detailedly exposed, dipping eastward (consistent with the slope direction).

Based on the analysis of existing main structural planes, the overall stability of the rock slope in Zone B is slightly better than that of Zone A, but it still falls under basically stable to marginally stable. Under external forces such as rainfall infiltration and vibration, the falling of irregular blocks formed by the intersection of multiple joint sets is the main risk. Construction excavation disturbance may activate new potential sliding surfaces.

4. Comprehensive Slope Stability Evaluation and Zoning

Based on the combined results of quantitative calculation and qualitative analysis, a systematic evaluation and zoning of the slope stability for the Huitong County Bamboo Industrial Park project is conducted:

1) The site slopes are generally in a marginally stable state under natural conditions and in an unstable state under saturated conditions due to heavy rain. Slope treatment is highly necessary and urgent.

2) Circular sliding within the miscellaneous fill is the main failure mode in Zones A & B Soil Slopes. Failure modes combine circular sliding (soil part) and polygonal sliding along the soil-rock interface or within weathered rock in Zones A & B Soil-Rock Slopes. Wedge-shaped collapse/sliding and planar sliding along outward-dipping gently inclined structural planes are the main failure modes, accompanied by weathering spalling and rockfall in Zones A & B Rock Slopes.

3) Key Treatment Zone (Zone I), includes all slope sections in Zone A and areas in Zone B with thick fill and high slopes. This zone is adjacent to important facilities (power poles, roads, factories), has poor stability and high-risk grade, requiring priority implementation of strong support measures.

4) Secondary Key Treatment Zone (Zone II), the soil-rock and rock slope sections in Zone B. Stability in this zone is relatively slightly better, but instability risks remain, requiring reliable protection and reinforcement measures.

5) General Protection Zone (Zone III), local areas with lower slope heights and relatively intact rock mass. Focus on slope surface protection, drainage, and greening.

5. Construction of a Comprehensive Slope Treatment System

Based on the principles of “safety and reliability, technical feasibility, economic rationality, and environmental harmony,” a four-in-one comprehensive treatment system of “Support and Reinforcement + Drainage and Protection + Ecological Restoration + Monitoring and Early Warning” is constructed.

5.1 Recommendations for Differentiated Support Design by Zone

5.1.1 Zone A (Key Treatment Zone)

Given the presence of important structures near the slope crest and limited space, a “row of piles (or bored cast-in-place piles) + pre-stressed anchor cables” pile-anchor support system is recommended. Piles need to be embedded into the lower stable rock layer to provide strong anti-sliding and anti-overturning capacity in soil/soil-rock slope sections.

In rock slope sections, a combined scheme of “systematic (or active) protective netting + local rock bolt (cable) reinforcement + toe retaining wall” is adopted. Protective netting prevents shallow collapses and spalling; bolts (cables) reinforce potential unstable wedges; the toe wall bears rockfall and protects the slope toe.

Displacement of power poles must be strictly monitored throughout construction at areas near power poles. Develop specialized support and monitoring plans. Methods like micro-piles or grouting reinforcement may be needed to pre-reinforce the power pole foundation area.

5.1.2 Zone B (Secondary Key and General Protection Zones)

At High-Steep Soil Slopes, where conditions allow, adopt "cut-back slope + lattice beam anchor (cable) with grass planting for slope protection." Where space is limited, use "buttress or cantilever retaining walls."

At Soil-Rock/Rock Slopes, recommend "cut-back slope + anchor (cable) lattice beam slope protection" or "stepped slope + ecological bag slope protection." Targeted bolt reinforcement should be applied to identified unstable wedges.

All Areas, must strictly implement construction sequences of "top-down method" or "layered and segmented excavation with support." Digging to full depth in one go is strictly prohibited.

5.2 Design of Three-Dimensional Interception and Drainage System

Water management is fundamental; a complete surface and subsurface drainage network must be established. Install permanent concrete interception ditches to block external runoff at slope crest. Set platform drainage ditches and chutes combined with support structures; install drainage holes on the slope face. Improve drainage ditches to ensure collected water is discharged smoothly from the site at slope toe. For areas with abundant groundwater, consider installing inclined drainage holes.

5.3 Ecological Restoration and Landscape Integration

Under the premise of ensuring safety, actively adopt ecological slope protection technologies. For slope protection forms like anchor lattice beams and ecological bags, plant grass/shrubs with imported soil within the frames or on the bags. Select local, well-adapted plant species with developed root systems to achieve rapid revegetation and soil/water conservation. Integrate slope treatment with the park's landscape design to form a green ecological barrier.

5.4 Full Life-Cycle Monitoring and Early Warning System

Implement information-based construction and long-term health monitoring. Horizontal/vertical displacement of slope crest and support structures, deep horizontal displacement (inclinometer), anchor (cable) stress, groundwater level, rainfall, crack development, etc. Increased frequency during construction (e.g., daily), regular intervals during operation (e.g., monthly), and real-time monitoring during special conditions like heavy rain. Establish three-level warning thresholds (warning, alert, alarm) and develop emergency response plans. The monitoring period should last at least two hydrological years after project completion. Achieve real-time analysis and dynamic feedback of monitoring data to guide possible adjustments in dynamic design, truly realizing "dynamic design and information-based construction."

6. Conclusion

1) The slopes at the Huitong County Bamboo Industrial Park have complex geological conditions, composed of loose fill, soft rock, and rock masses controlled by multiple structural plane sets, exhibiting poor self-stability.

2) Quantitative calculations using the Limit Equilibrium Method show that the slopes are marginally stable under natural conditions, with safety factors all below 1.0 under saturated conditions. Heavy rain is the decisive external factor leading to overall instability.

3) Qualitative analysis using stereographic projection reveals that rock slopes have multiple sets of unfavorable structural plane combinations, prone to wedge failure and planar sliding, with high

local collapse risk.

4) Based on the multi-method coupled comprehensive stability evaluation, the slopes are divided into key and secondary key treatment zones. Differentiated, combined support schemes are proposed, emphasizing active reinforcement measures like pile-anchors, lattice anchors, and protective netting.

5) A comprehensive treatment system encompassing support, drainage, ecology, and monitoring is constructed. Among these, whole-process, comprehensive monitoring and early warning is an indispensable key link to ensure engineering safety.

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