

Slope Stability Analysis and Remediation Measures in the Three Gorges Reservoir Area: A Case Study of a Soil–Rock Mixed Slope in Zhongxian County

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Abstract: This study investigates a soil–rock mixed slope in the Dongxi Community resettlement area of Zhongxian County, Three Gorges Reservoir region, based on field investigation and the strength reduction method (SRM) to evaluate its natural stability and verify the effectiveness of anti-slide piles reinforcement. The slope is 16–18 m high, with upper fill and silty clay overlying sandstone and mudstone. The fill roadbed at the crest has undergone a collapse zone of approximately 20 m×3 m, accompanied by cracking and retaining wall damage. Under natural conditions, the factor of safety (Fs) is 1.06 and the maximum displacement is 4.82 cm, indicating a basically stable state with insufficient reserve, while plastic deformation concentrates near the steep crest section. After installing 14 rock-socketed anti-slide piles (20 m in length, 5 m spacing, 8 m embedment into bedrock), Fs increases to 1.42 and displacement drops to 0.006 cm, representing a 34.0% improvement and a 99.9% reduction, respectively; both the localized deformation and plastic zone expansion are significantly restrained. The results demonstrate that anti-slide piles can effectively enhance the load-transfer mechanism of such soil–rock slopes. For long-term performance under reservoir operations and rainfall, complementary drainage systems and dynamic deformation monitoring are recommended. This study is conducted only on a single engineering site, so its results are mainly applicable to slopes with similar geological, geometric and hydrological conditions. It should be noted that the coupled effects of rainfall infiltration and reservoir water-level fluctuation were not explicitly simulated in the numerical analysis, as this study focused on the dry natural condition; this limitation should be addressed in future work.

Keywords: Three Gorges Reservoir area; Soil-rock slope; Strength reduction method; Stability analysis; Anti-slide piles; Treatment measures

Introduction

The terrain in the Three Gorges Reservoir Area is highly undulating, with complex geological structures. The periodic rise and fall of the reservoir water level and the concentrated seasonal rainfall superimpose on each other, causing the artificial excavation slopes along the reservoir banks and in the urban construction areas to remain in a state of complex stress adjustment and dynamic changes in the hydrological environment for a long time. Once such slopes lose stability, they not only directly threaten the safety of the slope itself but also may affect the safety of related infra-

structure and the lives and property of residents. Therefore, the stability assessment and engineering treatment of such slopes have always been one of the core issues in the research on disaster prevention and mitigation in the reservoir area [1]. Regarding the stability of slopes, scholars at home and abroad have conducted extensive research on aspects such as stability discrimination, identification of potential sliding surfaces, analysis of failure modes, and design of retaining and reinforcement structures, forming a relatively systematic theoretical framework and engineering practice system [2,3].

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The strength reduction method (SRM) is widely used in various slope stability evaluations and reinforcement designs due to its ability to simultaneously calculate the safety factor and reveal the characteristics of potential sliding surfaces. Liu Jian et al. [4] and Liu Xiaoguang [5] verified the effectiveness of SRM in identifying the deformation characteristics of slopes; Li Jian [6], Huang Feng [7], and Xu Wencheng [8] further expanded it to the optimization of reinforcement schemes for inclined layers and adverse geological high slopes. Moreover, rainfall infiltration significantly increases the soil moisture content, increases pore water pressure, and reduces shear strength, which are key factors in triggering slope instability; Li Lifeng et al. [9] and Fan Xin [10] explored the evolution mechanism of soft soil and mountain road slopes under rainfall conditions and proposed corresponding drainage and treatment measures; Yan Zhenlong [11] revealed the deep mechanism of the response of slopes to changes in hydrological conditions.

In terms of engineering treatment, anti-slide piles and anchoring structures are commonly used to treat adverse geological slopes. Jin Shengran [12] proposed a retaining and reinforcement scheme for high-fill soil slopes in the Three Gorges Reservoir Area; Gao Xilian et al. [13], Liu Pengjun [14], and Zhang Youqi et al. [15] conducted in-depth discussions on the applicability of different reinforcement technologies in open-pit mines and high slopes of roads; Shen Juncai [16], Sun Bin [17], and Yao Chuanshen [18] proposed a comprehensive treatment strategy based on the deformation mechanism and emphasized the importance of long-term monitoring and protection in ensuring the effectiveness of reinforcement.

However, existing studies mostly focus on the stability calculation of single slope types or the reinforcement effect of a single measure. For the "soil-rock" combined structure slopes in the urban relocation areas of the reservoir area, the systematic research combining "on-site failure signs - numerical stability analysis - verification of anti-slide piles treatment" is still insufficient. Therefore, this paper takes a partially collapsed rock and soil slope in a certain relocation area of Dongxi Community in Zhongxian County, Chongqing as the research object. Based on on-site investigation and parameter testing, the natural condition stability state is quantitatively evaluated using the strength reduction method; then, a comprehensive treatment scheme with anti-slide piles as the main body, combined with interception drainage and dynamic monitoring, is proposed, and the changes in displacement and stress fields before and after reinforcement are compared and analyzed. The research results aim to reveal the instability mechanism of such slopes and verify the effectiveness of the treatment scheme, providing a reference for the stability evaluation and prevention of similar projects in the Three Gorges Reservoir Area.



Figure 1 | Schematic diagram of the distribution location of the study slopes

Project Overview

Basic characteristics of the slope

The slope of the relocation area in Dongxi Community, Dongxi Town, Zhongxian County was formed by the excavation for urban relocation construction. It is a rock and soil slope located behind the still-rebuilding houses on Jiangwei Road in Dongxi Community. The slope is generally linear in shape, with a slope direction of approximately 275° . The slope length is about 50 meters, and the slope height is 16 to 18 meters. According to the "Technical Code for Slope Engineering in Buildings" (GB 50330-2013), this slope belongs to grade II to III and has a safety level of grade II. It should meet the corresponding stability requirements during the design service life. The slope area is approximately 1,060 square meters. The slope is steep at the top and gentle at the bottom, with an upper slope angle of about 80° to 90° and a lower slope angle of about 30° . The top of the slope is a road, and the bottom is a residential area and vegetable field. It has the characteristic that the load at the top of the slope and the affected area of the residential area at the bottom are large. The distribution location of the slope is shown in Figure 1.

Engineering geology conditions

The study area is located in the near-coastal valley slope zone of the Yangtze River. The terrain is a structurally eroded hilly area, with the general topography being higher in the south and west and lower in the north and east, with an elevation of approximately 262 to 280 meters. The site is mainly composed of the Quaternary Holocene artificial fill layer (Q4s) and residual alluvial layer (Q4el+dl), with the underlying Jurassic Upper Penlee Town Formation (J3p) bedrock. The artificial fill is brownish-yellow, loose to slightly dense, mainly consisting of silt clay intermixed with



Figure 2 | Full view of the slope site



Figure 3 | Slope top roadbed collapse and pavement deformation

Table 1 | Physical and Mechanical Parameters of Rock and Soil Masses

Soil layer	Natural unit weight $\gamma/(\text{kN}\cdot\text{m}^{-3})$	Saturated unit weight $\gamma/(\text{kN}\cdot\text{m}^{-3})$	Elastic modulus E/MPa	Cohesion c/kPa	Internal friction angle $\phi/(^{\circ})$	Permeability coefficient k/(cm/s)
Clay with silt content	19	19.5	30	22	21	1.0×10^{-5}
Clay with silt content mixed with gravel	19.5	20	35	23	22	1.5×10^{-5}
Strongly weathered sandstone	21	21.2	4.0×10^4	28	25	1.0×10^{-7}

gravel, with the gravel content ranging from 20% to 40%. The exploration reveals a thickness of 5 to 7 meters. The residual alluvial layer is brownish-yellow silt clay inter-mixed with a small amount of sandstone and mudstone gravel, with a thickness of 0.8 to 2 meters. The bedrock mainly consists of feldspar quartz sandstone, siltstone mud, and mud-sandstone.

The uniformity of the fill roadbed at the top of the slope is poor. It is loose to slightly dense, and the contact conditions between the upper soil layer on the slope and the underlying bedrock are complex, which is the main weak part controlling the slope deformation. Field investigation shows that the fill roadbed at the top of the slope has already collapsed for about 20 meters in length and about 3 meters in width, causing pavement cracking and damage to the outer retaining wall; under the continuous rainfall, the slope may further undergo soil deformation and extend deeper. The overall view of the slope site is shown in **Figure 2**, and the collapse of the top roadbed and pavement deformation are shown in **Figure 3**.

Physical and mechanical parameters of rock and soil mass

Based on the results of the investigation and geotechnical tests, the main rock and soil parameters adopted for calculation are shown in **Table 1**. These parameters include natural density, saturated density, elastic modulus, cohesion, internal friction angle, and permeability coefficient, which provide a basis for the numerical analysis of slope stability.

All mechanical parameters in **Table 1** were derived from the approved geotechnical investigation report for the Dongxi Community resettlement area, complemented by laboratory direct shear and consolidation tests on undisturbed samples, as well as in-situ double-ring infiltration tests for permeability coefficients. No additional sensitivity analysis or parameter calibration was performed, as the parameters were directly adopted from the site-specific investigation report for this project.

Slope Stability Evaluation
Calculation method and evaluation criteria

Based on the two-dimensional plane strain model of the critical cross-section, Numerical analyses were carried out using MIDAS GTS NX (v. 2021) based on a 2D plane-strain model along the critical cross-section. The model is 200 m in horizontal extent, with left and right boundary heights of 120 m and 40 m, respectively. The mesh comprises 5,171 elements and 5,033 nodes, with local refinement near the slope crest, fill-bedrock interface, and potential slip zone. Roller supports were applied to lateral boundaries and fixed supports to the bottom. The Mohr-Coulomb failure criterion with a non-associated flow rule was adopted for all geomaterials. The analysis was performed under dry natural conditions; rainfall and reservoir effects were not explicitly modeled. The strength reduction method (SRM) was applied by simultaneously reducing c and tanφ. The critical safety factor F_{s_s} was determined when (1) the unbal-

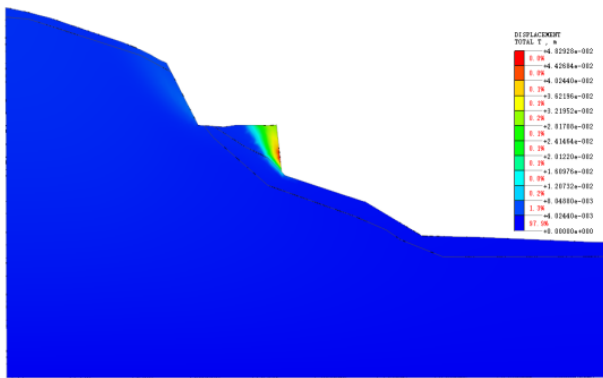


Figure 4 | Slope displacement cloud map under natural conditions

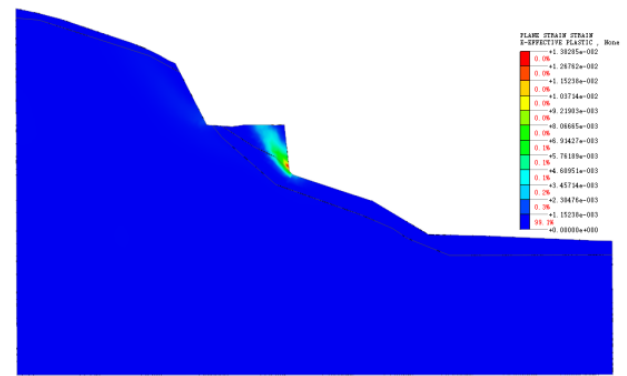


Figure 5 | Distribution Map of the Plastic Zone on the Slope under Natural Conditions

Table 2 | Classification Table of Landslide Stability States

Landslide stability state	Unstable	Under-stable	Basically stable	Stable
Landslide stability coefficient F_s	$F_s < 1.0$	$1.0 \leq F_s < 1.05$	$1.05 \leq F_s < 1.15$	$F_s \geq 1.15$

anced force ratio exceeded 1.0×10^{-3} , (2) displacement increments failed to converge within 500 iterations, and (3) a continuous plastic strain band formed through the slope. the transient effects of rainfall infiltration and reservoir water-level fluctuation were not explicitly simulated in this stage due to the lack of long-term hydrological monitoring data at the specific site. This constitutes a limitation of the present study.

To simulate the stress state of the original slope, only the gravitational load and automatic constraints were applied under natural conditions. The displacement cloud map (Figure 4) and the plastic zone state map (Figure 5) were obtained through the strength reduction method (SRM). Through calculation and analysis, the safety factor F_s of the slope was determined to be 1.06. According to the "Design Specifications for Prevention of Landslides on Highways" (JTG/T 3334-2018), the stable state of the landslide under natural conditions can be determined according to Table 2.

Natural condition calculation results

Under natural conditions, the maximum displacement of the slope is approximately 4.82 cm, and the safety factor F_s is 1.06. The displacement cloud map shows that the major deformation is concentrated at the fill roadbed at the top of the slope and the junction between it and the underlying soil and bedrock; the plastic zone is also mainly developed near the steep slope section at the top of the slope, indicating that the local deformation of the slope has obvious shallow control characteristics and there is a possibility of extending to the deeper part. This result is basically consistent with the phenomena of slope top roadbed collapse, pavement cracking and retaining wall damage at the site.

Stability analysis

The calculation results indicate that the natural state of the slope has not reached the condition of overall instability, but $F_s = 1.06$ is only slightly higher than the basic stability limit, and the stability reserve is limited. Considering the existing deformation at the site, it can be concluded that the slope is in a state of approximately basic stability in the calculation and is relatively sensitive in the engineering aspect. Continuous rainfall may lead to an increase in the water content of the slope, an increase in the soil weight, and a decrease in the shear strength, thereby further weakening the stability of the slope. Therefore, the basic stability under the natural condition does not mean that the slope has sufficient safety reserve. Active reinforcement and drainage measures should be taken to reduce the potential risk of instability.

Treatment Measures and Effect Evaluation

Treatment plan

Based on the stability analysis results in Chapter 3, the study found that the slope was in a basically stable state but with a low safety reserve under natural conditions. The top of the slope had already shown significant deformation and failure. To control further deformation of the slope body and ensure the safety of the road at the top and the residential area at the foot of the slope, targeted reinforcement measures were required. This chapter combines the safety factor F_s , the engineering geological conditions of the slope, and the deformation characteristics to propose a treatment plan with anti-slide piles as the main reinforcement measures. The treatment effect was evaluated through a comparative analysis of F_s and displacement before and after reinforcement.

Considering the slope height, slope surface shape, distribution of the road at the top and the residential area at the

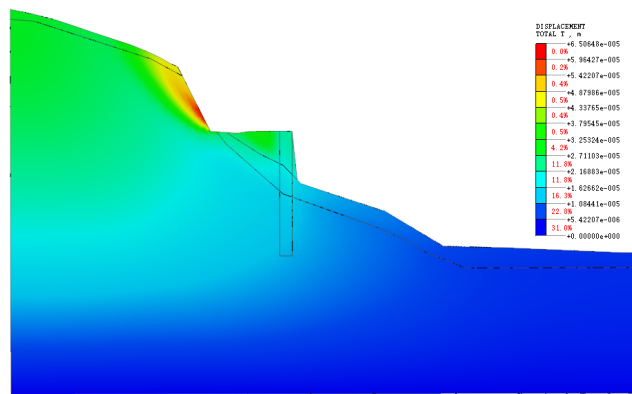


Figure 6 | Displacement cloud map of the slope after the anti-sliding pile treatment

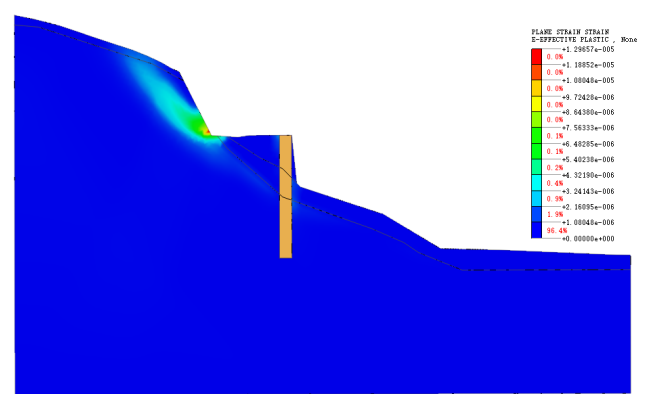


Figure 7 | Distribution Map of Plastic Zone on Slope after Anti-slip Pile Treatment

foot of the slope, anti-slide piles were adopted as the main reinforcement measures. The anti-slide piles were arranged along the slope surface, with a total of 14 piles, constructed using manual bored piles. The cross-sectional dimensions of the piles were approximately $1.5 \text{ m} \times 2.0 \text{ m}$, with a length of about 20 m and a center distance of 5.0 m; approximately 8 m were embedded in the stable rock layer, approximately 4 m were in the soil layer, and about 8 m were exposed above the ground. The anti-slide piles formed a reliable anti-slide fulcrum by embedding in the stable rock layer, transferring the sliding thrust generated by the potential sliding body to the stable stratum, thereby enhancing the overall anti-slide capacity of the slope.

Considering that the studied slope has both the road at the top and is located in a reservoir area with significant rainfall influence, the construction of anti-slide piles should be carried out in coordination with slope surface drainage, road top water interception, and deformation monitoring. The top of the slope should avoid direct surface water entering the fill layer, the slope surface should be promptly drained and collected, and existing cracks and retaining wall deformations should be continuously monitored.

In the numerical model, the anti-slide piles were simulated using beam elements with elastic behavior. The elastic modulus was 30 GPa (C30 concrete) with a Poisson's ratio of 0.2. The cross-sectional dimensions ($1.5\text{m} \times 2.0 \text{ m}$) were assigned as section properties. Pile-soil/rock interaction was modeled via interface elements, with interface shear strength parameters set to 0.8 times the corresponding soil/rock strength. Pile bases were rigidly fixed within the stable bedrock (embedment depth $\approx 8 \text{ m}$), and pile heads were free. The sliding thrust from the potential sliding mass was transferred through the interface to the stable stratum.

Evaluation of treatment effect

From the analysis results of the post-treatment values, it can be seen that after the anti-slide piles were set, the pile body penetrated the potential deformation zone and extended into the stable rock layer, providing significant constraints on the slope deformation; the high deformation ar-

eas at the top of the slope and the steep slope section were significantly reduced, and the continuous development of the plastic zone was suppressed. Quantitative results show that the slope safety factor F_s increased from 1.06 in the natural condition to 1.42, an increase of 0.36, with an increase of approximately 34.0%; the maximum displacement decreased from 4.82 cm to 0.006 cm, a reduction of approximately 99.9%. After the treatment, $F_s \geq 1.15$, meeting the stable state classification standard adopted in this paper, indicating that the anti-slide piles can effectively change the force path of the potential sliding body and transfer part of the sliding force to the stable rock layer, thereby improving the overall anti-slide capacity of the slope.

The comparison of calculation indicators before and after reinforcement is shown in **Table 3**. Both the safety factor F_s and the maximum displacement have been significantly improved, indicating that the anti-slide piles treatment scheme adopted is well adapted to the deformation characteristics of the studied slope. However, considering the long-term effects of rainfall in the Three Gorges Reservoir area and the road load at the top of the slope, the engineering treatment should still be implemented in coordination with slope water interception, slope surface drainage, and deformation monitoring to control the risks of water-induced softening and continuous deformation.

The two displacement values were obtained under strictly comparable numerical conditions—identical mesh, boundary conditions, material properties, and convergence criteria—with the presence of anti-slide piles as the sole variable. The units have been verified as centimeters. The post-reinforcement displacement ($0.006 \text{ cm} \approx 0.06 \text{ mm}$) reflects the rigid restraint provided by the rock-socketed piles, which almost completely suppresses downslope movement under the quasi-static design load. However, this value should be interpreted as an indicator of reinforcement effectiveness under the specific calculation scenario rather than a precise prediction of absolute field displacement, as time-dependent creep and cyclic reservoir loading are not accounted for.

Table 3 | Comparison of Calculation Results Before and After Slope Reinforcement

Working condition	Safety factor F_s	Maximum displacement / cm	Stability state
Natural condition	1.06	4.82	Basically stable
After anti-slide piles reinforcement	1.42	0.006	Stable

Applicability of treatment measures and construction control

For the anti-slide piles in this project, a larger embedded rock depth is adopted, which can enhance the interaction between the pile and the rock and form a reliable anti-slide support point. During the construction process, the pile position, pile diameter, pile length, and embedded rock depth should be carefully controlled. Measures should be taken to strengthen the stability of the hole walls and handle ground-water issues to avoid local instability caused by construction disturbances. For the parts at the top of the slope that already have cracks and damaged retaining walls, safety isolation and temporary protection should be implemented first, followed by reinforcement construction. After the treatment is completed, a monitoring system should be established, with the main contents including displacement at the slope top, cracks on the slope surface, deformation of the anti-slide pile, and the operation status of the drainage facilities.

Conclusion

The study focused on a typical rock and soil mixed slope formed by the excavation for urban construction in a reservoir area. The fill roadbed at the top of the slope has experienced significant local damage. The on-site deformation signs are consistent with the calculation results of SRM ($F_s = 1.06$, maximum displacement 4.82 cm), indicating that although the slope has not completely failed, its stability reserve is insufficient and it has sensitivity to further deformation development.

After using 14 large-section rock-embedded anti-slide piles for active support, the safety factor of the slope increased to 1.42, the maximum displacement decreased to 0.006 cm, and the expansion range of the plastic zone significantly contracted. This confirmed that the anti-slide piles could effectively cut off the potential sliding surface, transfer the sliding thrust to the stable rock layer, and significantly improve the stress state of the slope.

The research results revealed the deformation control mechanism of this type of "upper soil, lower rock" slope under natural conditions and verified the effectiveness of the anti-slide piles treatment scheme. However, considering the long-term effects of periodic rainfall and traffic loads on the top of the slope in the Three Gorges Reservoir area, it is recommended that the governance system should integrate slope top water interception, slope surface drainage, and long-term displacement-crack-pile strain collaborative monitoring to forming a comprehensive protective strategy of

"active reinforcement – hydrological regulation – dynamic feedback." However, since the numerical analysis was performed under dry natural conditions without explicit modeling of rainfall or reservoir level fluctuations, the effectiveness of the proposed measures under coupled hydrological loading should be further validated through future monitoring data and transient seepage-stability analyses.

This study presents a site-specific case investigation. The quantitative results (e.g., safety factors, displacement values, and pile dimensions) are directly applicable only to slopes with geological, geometrical, and hydrological conditions comparable to those of the Dongxi Community site. For other slopes, the proposed methodological framework—combining field investigation, SRM numerical analysis, and anti-slide pile verification—is transferable; however, the specific design parameters should be re-evaluated based on local conditions. The effectiveness of the reinforcement scheme should also be validated through site-specific monitoring and transient hydrological analyses before direct application to other projects.

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