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Research on stability of a highway high slope based on the finite element analysis of the section size and anchorage depth of the anti-slide pile

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Technical Note

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Abstract

This paper took a typical high-slope project of a mountainous highway in Deyang City, China, as the research subject, and conducted a sensitivity analysis of anti-slide pile support parameters based on finite element numerical simulation. This slope is located on the eastern edge of the Longmenshan Fault Zone, with large topographic fluctuations and strongly weathered rock and soil masses. There have been multiple shallow landslides in history, posing a potential threat to road traffic safety. To scientifically evaluate the effectiveness of the support scheme, the research first constructed a finite element model based on the on-site engineering geological survey data. The model used the Mohr-Coulomb elastoplastic constitutive relationship to describe the soil behavior. The anti-slide pile structure was simulated by linear elastic beam elements, and the nonlinear interaction between the pile and the soil was accurately characterized through the contact interface elements. Before the formal parameter analysis, the effectiveness of the constructed finite element model was verified. Then, the slope stability was tested when the cross-sectional diameter of the piles was 1, 2, 3, 4, and 5 m, and the anchorage depth was 3, 4, 5, 6, and 7 m. The final results showed that the finite element model can effectively simulate the high slope. Increasing the cross-section and anchorage depth of the anti-slide piles could improve the slope stability, but after a certain point, the enhancement effect was no longer significant. Therefore, a cross-sectional diameter of 3 m and an anchorage depth of 5 m were finally selected.

1. Introduction

With the continuous advancement of transportation infrastructure in China, especially in the western mountainous and hilly regions, highway engineering will inevitably face the problem of excavation and support of high slopes (Tian et al., 2024; Ahmadi, 2022). Among various slope support techniques, anti-slide piles are used for stabilizing high slopes due to their high load-bearing capacity, broad applicability, relatively flexible construction, and little disturbance to the surrounding environment. Anti-slide piles are usually installed in rows along the mid-lower part of a high slope's sliding surface (Ren et al., 2021). They utilize the anchoring effect generated by embedding into the stable rock and soil area to resist the thrust transmitted by the upper sliding body, thereby enhancing the overall stability. The design parameters of anti-slide piles, namely their total length and embedded depth, directly affects both support effectiveness and project cost (Wen et al., 2025). If anti-slide piles are too short or insufficiently embedded, it will be difficult to effectively maintain slope stability. Hence, accurate design of these parameters is essential. Most traditional design methods rely on limit equilibrium theory, which involves simplifying the slope thrust before determining anti-slide pile parameters. Although easy to implement, these methods are unable to precisely capture the complex interaction mechanisms among the slope, soil, and piles (Han et al., 2023). In contrast, finite element analysis, as a numerical simulation technique, can be used to establish continuous medium models for slopes and anti-slide piles. This approach can simulate the constitutive behavior of the rock-soil mass, pile-soil contact, load transfer paths, and deformation compatibility, thereby offering a more precise assessment of how pile length and embedment depth influence slope stability. Moreover, within a finite element framework, parameters related to the piles and the slope can be readily adjusted to simulate a variety of geological and loading scenarios (Liu et al., 2020). Jose et al. (2025) used PLAXIS 3D, a finite element software, to conduct a numerical analysis of reinforced anti-slide piles, evaluating

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their performance in landslide control. Zhang et al. (2024) used centrifugal model tests to study the load-bearing behavior of h-pile reinforced slopes composed of soil-rock mixtures under rainfall conditions. Meanwhile, Gang et al. (2019) investigated the reinforcement effect of anti-slide piles combined with prestressed anchor cables on slopes. The above relevant studies have all conducted research and analysis on anti-slide piles. Some researchers used finite element software to analyze the performance of anti-slide piles, some used actual models to analyze it, and some focused their research on tools to assist the performance of anti-slide piles. This paper also used a finite element model to analyze it, verified the numerical model with an actual high slope, and then used a finite element numerical model to test the slope stabilization performance of anti-slide piles. With the help of the finite element numerical model, the parameters of anti-slide piles can be simulated, eliminating the need for time-consuming and laborious testing of physical models. The result data obtained from the simulation can provide effective data reference for the actual construction of anti-slide piles. This paper took a high slope along a highway in Deyang City, Sichuan Province, China, as an example to analyze the impact of the circular section size of anti-slide piles and their anchorage depth on slope stability through a finite element model.

2. Slope anti-slide pile support mechanism

With the continuous implementation of China's Western Development Strategy and the rapid expansion of mountainous expressways, high and steep slope engineering has increasingly become a key technical challenge in highway construction. Under the influence of complex geological conditions, high slopes are highly prone to sliding, collapse, or creep instability, which seriously threatens road operation safety and people's lives and property. To effectively control slope deformation and improve overall stability, anti-slide piles, as a deep foundation retaining structure, have been widely used in the treatment projects of highway high slopes due to their advantages such as high bearing capacity, clear construction boundaries, and minimal disturbance to the environment. Anti-slide piles are usually installed vertically or slightly inclined at the front edge or middle of the landslide mass, as shown in Figure 1. The working state of anti-slide piles can be divided into two mechanical regions. The part above the sliding surface is the loaded section, where the anti-slide pile will bear the lateral thrust from the sliding mass. This thrust is formed by the comprehensive action of the gravity component of the sliding mass, pore water pressure, seismic inertial force, etc. The part below the sliding surface is the anchorage section. This part is embedded in the stable stratum and relies on the passive resistance provided by the surrounding rock and soil mass to balance the upper bending moment and shear force. Under the ultimate equilibrium state, the anti-slide pile can be regarded as a hyperstatic beam with one end free and the other end fixed, and its deformation presents an S-shaped curve, with the upper part protruding in the sliding direction of the sliding mass and the lower part bending in the opposite direction. The thrust of the sliding mass in the slope is not concentrated at a certain point of the anti-slide pile but is non-linearly distributed along the height of the loaded section. In the classical theory, it is usually assumed to be distributed in a triangular, trapezoidal, or parabolic shape, and the actual distribution is affected by the properties of the sliding mass, sliding speed, and pile spacing.

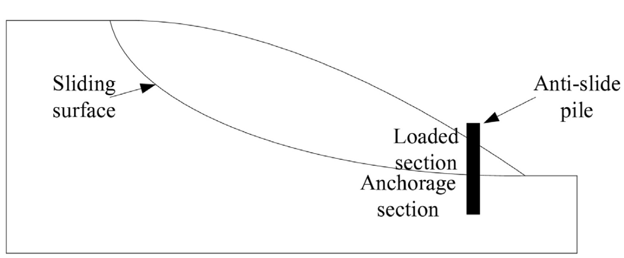

Figure 1. The slope-anti-slide pile diagram.

The supporting performance of anti-slide piles is essentially determined by the mechanical behavior of the pile-soil cross-section. In the loaded section, the sliding mass exerts active earth pressure on the pile. The displacement of the pile body triggers the soil arching effect, causing part of the thrust to bypass the pile body and be transferred to both sides, thereby reducing the load on a single pile. In the anchorage section, when the pile body displaces in the moving direction of the sliding mass, the soil in front enters the passive limit state and provides reverse resistance. The friction coefficient and roughness of the sliding surface, as well as whether grouting around the pile is set, will all affect the shear transfer efficiency and the coordinated deformation ability. The anchorage section can provide anti-overturning moment, enhance the bearing resistance of the pile section, and restrain the rotation of the pile bottom. Anti-slide piles not only bear local loads but also improve the overall safety factor of the slope by restricting the displacement of the sliding mass.

3. Case analysis

3.1 Project overview

This paper analyzes a high slope along a highway in Deyang City, Sichuan Province. The slope is located in a hilly area, and its cross-section diagram is presented in Figure 2. It has a steep incline and a relatively flat top, with a slope angle between 20° and 40°. The slope extends 120 meters horizontally, with a toe height of 30 m and a length of 12 m, and a crest height of 60 m with a length of 20 m. From top to bottom, the soil is composed of a silty clay layer, a landslide deposit layer (Wang et al., 2023), and a common clay layer.

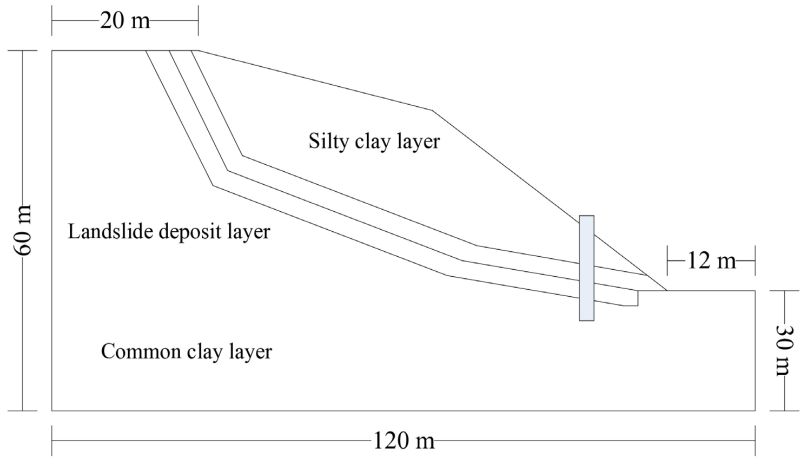

Figure 2. Schematic diagram of the highway high slope and anti-slide pile section.

Table 1. Relevant parameters of the numerical model of highway high slope.

Structural layer	Silty clay layer	Landslide body soil layer	Ordinary clay layer
Grid setting	1,325 element meshes	1,896 element meshes	2,598 element meshes
Unit weight (kN/m)	21	22	21
Cohesion (kPa)	19	17	14
Internal friction angle (°)	25	20	15
Elastic modulus (MPa)	26	31	21
Poisson's ratio	0.31	0.29	0.25
Initial stress field	Use the self-weight stress field		
Physical properties of the anti-slide pile	Ideal elastoplastic body (Wang et al., 2020)		
Physical properties of soil mass	Ideal elastoplastic body		
Model upper boundary condition	Free boundary		
Boundary condition of both sides of the model	Normal constraint		
Model bottom boundary condition	Fixed constraint (Ma et al., 2019)		
Normal connection of the pile unit and slope unit	Spring coupling (Li et al., 2023)		
Tangential connection of the pile unit and slope unit	Spring coupling		

3.2 Model parameters

FLAC software was employed to construct a finite element numerical model for the highway high slope, and the relevant parameters of the model are listed in Table 1. As shown in Figure 1, the numerical model was structurally divided into a silty clay layer, a landslide deposit layer, and a common clay layer. The mesh consisted of 1,325 triangular elements for the silty clay layer, 1,896 for the landslide deposit layer, and 2,598 for the common clay layer. The model also included an anti-slide pile model, simulated using pile elements (Xu et al., 2022), and its related physical parameters included a pile spacing of 3 m, an elastic modulus of 35 MPa, a normal stiffness of 2.5×10^7 kN/m, and a Poisson's ratio of 0.2. The initial conditions of the model are shown in Table 1. The strength reduction method (Wang et al., 2021) was used during the simulation to calculate the safety factor of the slope.

3.3 Test items

(1) Validation of the high slope numerical model

To validate the high-slope numerical model, it was compared with an actual high slope. The circular cross-section diameter of the anti-slide piles in the actual slope was 3 m, the anchorage depth was 7 m, and the horizontal distance between the pile point and the slope toe boundary was 20 m. Sensors were installed along the main axis of a pile at 1 m intervals o collect shear force and bending moment. The sensors were numbered 1 to 7 from top to bottom. The data collected by the sensors was compared with the simulation results from the numerical model.

(2) The influence of the cross-sectional size of anti-slide piles

Upon validation of the high slope numerical model, the effect of the cross-sectional size of anti-slide piles on slope stability was tested. The horizontal distance from the pile tip to the slope toe boundary was maintained at 20 m, the pile depth was set to 5 m, and the section diameter was set to 1, 2, 3, 4, and 5 m, respectively. The stability was calculated.

(3) The influence of the anchorage depth of anti-slide piles

The pile tip was also positioned at a horizontal distance of 20 meters from the slope toe boundary. With the pile cross-section diameter fixed at 3 m, simulations were conducted with anchorage depths of 3, 4, 5, 6, and 7 m to calculate the slope stability under each configuration.

3.4 Test results

Before using the numerical model to analyze the stability of anti-slide piles with varying dimensions, its validity was tested by comparing the simulated pile behavior with shear force and bending moment measurements obtained from actual piles at the study site. It can be seen from Table 2 that the numerical results demonstrated general consistency with field observations. All the p values were greater than 0.05, indicating no statistically significant difference between the simulated and measured data. Therefore, the finite element numerical model is validated for simulating the behavior of the actual highway slope.

Following validation of the numerical model, the effect of pile cross-sectional diameter on slope stability was tested by leveraging the parametric flexibility of the numerical model. It can be seen from Table 3 that the safety factor of the slope increased with pile diameter and tended to stabilize. Meanwhile, both horizontal and vertical slope displacements showed minor reductions, while the maximum bending moment in the pile decreased. Moreover, the maximum shear force of the pile exhibited a trend of decreasing first and then increasing. It should be noted that the positive and negative signs in the values indicate direction rather than magnitude. When the diameter increased to 4 m, the stabilizing effect on the slope became stable gradually.

It can be seen from Table 4 that the safety factor of the slope increased with the increase of the anchorage depth and remained stable after the anchorage depth reached 5 m. The horizontal displacement of the slope decreased and then

Table 2. Verification results of the high slope numerical model.

Detection point	Shear force (kN)			Bending moment (kNm)		
	Actual slope	Numerical model	P value	Actual slope	Numerical model	P value
1	8.71 ± 0.11	8.76 ± 0.13	0.421	-69.8 ± 0.1	-69.7 ± 0.2	0.357
2	9.23 ± 0.12	9.27 ± 0.11	0.354	-62.3 ± 0.2	-62.4 ± 0.1	0.452
3	9.89 ± 0.21	9.82 ± 0.17	0.369	-56.8 ± 0.1	-56.7 ± 0.1	0.346
4	10.34 ± 0.15	10.39 ± 0.14	0.426	-49.7 ± 0.3	-49.6 ± 0.2	0.321
5	11.12 ± 0.12	11.17 ± 0.13	0.456	-40.1 ± 0.2	-40.7 ± 0.3	0.258
6	11.97 ± 0.11	11.99 ± 0.12	0.438	-32.5 ± 0.1	-32.1 ± 0.2	0.369
7	12.75 ± 0.11	12.79 ± 0.10	0.264	-27.6 ± 0.1	-27.2 ± 0.1	0.356

Table 3. Effects of circular section diameters.

Circular section diameter	1 m	2 m	3 m	4 m	5 m
Slope safety factor	1.09	1.11	1.23	1.42	1.49
Horizontal slope displacement (mm)	153	147	141	137	134
Vertical slope displacement (mm)	348	339	331	328	323
Maximum bending moment (kNm)	-70.3	-61.2	-54.3	-36.1	-35.7
Maximum shear force (kN)	-20.2	-22.3	15.8	16.9	16.4

Table 4. Effects of anchorage depth.

Anchorage depth	3 m	4 m	5 m	6 m	7 m
Slope safety factor	1.12	1.31	1.52	1.53	1.53
Slope horizontal displacement (mm)	200	196	192	201	202
Vertical slope displacement (mm)	402	355	341	340	339
Maximum bending moment (kNm)	-36.4	-44.9	-54.8	-58.9	-74.4
Maximum shear force (kN)	-37.2	-32.3	-39.4	-31.2	-27.5

increased, with little fluctuation, and remained stable after the anchorage depth reached 5 m. Similarly, the vertical displacement decreased first and remained stable after the 5 m threshold. The maximum shear force in the anti-slide pile demonstrated a tendency of decreasing first, then increasing, and finally decreasing again. The results suggest that increasing anchorage depth can reduce slope deformation and increase bending moments. Excessive anchorage depth will induce larger bending, and the deformation may lead to a reduction in shear capacity.

4. Discussion

During the construction of transportation infrastructure, highway high slopes are a key technical challenge. The reason is that under the combined effects of natural weathering, rainfall infiltration, seismic disturbances, and human excavation, high slopes are highly prone to geological disasters such as landslides and collapses, which seriously threaten road traffic safety and people's lives and property. How to scientifically and efficiently reinforce high slopes has become one of the core content of geotechnical engineering and highway construction. Among slope support structures, anti-slide piles are widely used in high slope protection projects due to their advantages such as high bearing capacity, good deformation control, convenient construction, and strong adaptability. The principle of anti-slide piles stabilizing high slopes is to provide uplift and bending resistance through the anchorage section that penetrates into the stable stratum and use the loaded section to resist the thrust of the sliding mass, thereby anchoring the unstable rock and soil mass. Traditional design methods usually ignore factors such as the non-linear contact between piles and soil, the softening effect of the slip zone, the coupling of groundwater seepage, and the three-dimensional space effect, resulting in design results that are either too conservative or lack sufficient safety. Finite element analysis method, with its powerful non-linear solving ability, multi-physical field coupling function, and accurate simulation ability of complex boundary conditions, has become an important tool for evaluating slope stability and the performance of support structures. In this paper, a finite element numerical model was used to analyze the influence of the cross-sectional size and anchorage depth of anti-slide piles on slope stability.

The effectiveness of the finite element numerical model was verified through the test results of the actual slope and pile-anchor system. Increasing the cross-sectional size of anti-slide piles can enhance the stability of slopes, but there is a marginal effect. Increasing the anchorage depth of anti-slide piles will first increase and then decrease the slope stability. The reason is that increasing the cross-sectional size of anti-slide piles enhances their flexural performance and the reduction in their deformation also leads to a decrease in the deformation of the slope. When the anchorage depth of anti-slide piles increases, the bending moment they bear also increases. An over-bent anti-slide pile will result in the loss of internal shear force and then break.

5. Conclusions

In this paper, a case study was conducted on a highway high slope in Deyang City, Sichuan Province. The finite element model was used to analyze the effects of the circular section size and anchorage depth of anti-slide piles on the slope stability. It was found that the shear force and bending moment in the piles obtained from the finite element model were essentially consistent with field measurements from the actual slope, and there was no significant difference between them. Moreover, increasing the section size of the pile effectively reduced the slope deformation and negative bending moment, enhancing the slope safety factor; however, this stabilizing effect tended to be stable when the pile diameter exceeded 4 m. Increasing the anchorage depth of the pile reduced slope deformation, but the bending moment increased, resulting in internal shear loss and reduced slope stability. Therefore, an anchorage depth of 5 m is more appropriate.

The limitation of this paper lies in that it does not fully consider the influence of the spacing of row piles and the local geographical environment on the slope stability. Therefore, future research will further analyze it.

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Declaration of interest

The author declares no conflict of interest.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

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