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Research on Load Transfer Law of Combined Reinforcement Using Anchor Cable Frames and Anti-slide Piles: Dynamic Analysis Based on Pile-Soil Contact Stress

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Abstract: From the perspective of dynamic analysis of pile-soil contact stress, this paper investigates the load transfer law of combined reinforcement using anchor cable frames and anti-slide piles. It encompasses the load transfer mechanism of the combined reinforcement using anchor cables and anti-slide piles, collaborative design judgment, and long-term performance prediction. The aim is to provide a reference for subsequent collaborative design and its application, thereby ensuring the effectiveness of the combined reinforcement.

Keywords: Pile-soil contact stress; Anchor cable frame; Anti-slide pile; Combined reinforcement; Load transfer

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1. Introduction

The combined reinforcement using anchor cable frames and anti-slide piles offers advantages such as efficiency and adaptability, and has been widely applied in current slope stabilization projects. However, existing engineering practices often fail to clarify the specific load distribution mechanism between the two, neglecting the impact of soil-structure interface interactions on load transfer. This results in insufficient targeted collaborative design and makes the combined reinforcement system prone to fatigue failure under long-term cyclic loading [1]. To avoid such issues, researchers need to take the dynamic changes in pile-soil contact stress as the fundamental starting point, focusing on three basic directions: load transfer mechanism, collaborative design judgment, and long-term performance prediction. Scientific research should be conducted on the load transfer law to ensure the stability and durability of the combined reinforcement system.

2. Load transfer mechanism of combined reinforcement using anchor cable frames and anti-slide piles

2.1. Experimental design and data collection

To investigate the dynamic transfer law between anchor cable prestress and pile-soil contact stress of anti-slide piles, this study utilized typical landslide geology as a test sample, characterized by silty clay soil with a natural moisture content of 22%, cohesion of 28 kPa, an internal friction angle of 18°, and a dry density of 1.72 g/cm³. Based on these conditions, a 1:10 scale experimental model was constructed and validated through Midas/GTS finite element software simulations. During the experiment, low-relaxation high-strength steel strands with a diameter of 15.2 mm and a tensile strength of 1860 MPa were selected. Anti-slide piles were constructed using C30 reinforced concrete, with specifications of 200 mm × 200 mm × 2.5 m. Strain gauges and pressure sensors were deployed at the pile-soil contact interface to collect real-time data on contact stress, anchor cable prestress, and soil displacement. Loads were applied in stages, with each stage controlled at 50 kN and a holding time of 30 minutes, reaching a final load of 300 kN. Simultaneously, parameter changes were monitored at holding times of 1d, 3d, 7d, 14d, and 28d, with a focus on the impact of shear action between the soil and structural interface. During the experiment, data on anchor cable prestress loss, pile-soil contact stress distribution, and interface shear displacement were synchronously recorded, with environmental interferences such as temperature and humidity excluded to ensure data accuracy [2]. Three sets of parallel experiments were conducted, and the average values were used as the basis for subsequent analysis, focusing on the dynamic correlation between anchor cable prestress and pile-soil contact stress, as well as exploring the impact of interface shear action on load distribution. A three-dimensional model diagram is shown in **Figure 1**.

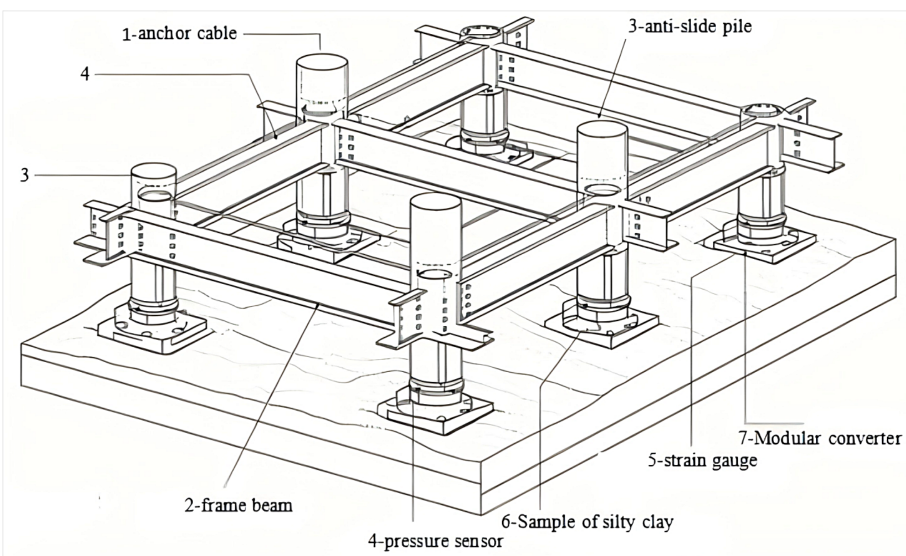

Figure 1. Three-dimensional schematic diagram of the scaled model of the joint reinforcement of the anchor frame and anti-slip pile

2.2. Analysis of dynamic transfer law

The experiment revealed that during the initial loading phase, the prestress in the anchor cables increased rapidly, with the concentrated area of pile-soil contact stress located in the middle to lower part of the pile, approximately 1.5–2.0 meters from the pile top. At this time, the soil was in the elastic stage, with minor shear displacement at the interface, not exceeding 0.3 mm. The main load was borne by the anchor cables, with the anti-slide piles accounting for only 30%–35% of the load, indicating an unstable load distribution between the two [3]. When the load was between 100–200 kN, the growth rate of the anchor cable prestress began to slow down, while the prestress loss gradually increased, reaching a cumulative loss rate of 8%–12%. The pile-soil contact stress began to spread to the upper part of the pile, and the shear displacement at the interface increased significantly, reaching 0.3–0.8 mm. At this point, the soil had entered the plastic stage, with strong shear action at the interface, and a significant portion of the load began to be borne by the anti-slide piles, accounting for 70%–80% of the load, while the load borne by the anchor cables decreased significantly. However, the load distribution was relatively balanced. The basic load distribution proportions are shown in **Figure 2**. When the load exceeded 200 kN, the prestress in the anchor cables reached a stable state, with a prestress loss rate of 12%–15%. The pile-soil contact stress was uniformly distributed along the entire pile, and the shear displacement at the interface remained stable at 0.8–1.0 mm. The soil had entered the plastic yielding stage, with stable shear action at the interface. At this time, the loads borne by the anti-slide piles and anchor cables were of similar magnitude, both ranging from 45%–55%, and remained stable, indicating good collaborative load-bearing performance between the two. Time-effect analysis showed that as the loading time increased, the anchor cables experienced greater prestress loss, while the pile-soil contact stress initially increased and then stabilized. During the first 1–7 days of loading, the anchor cables exhibited the fastest rate of prestress loss, and the pile-soil contact stress also increased rapidly, with a daily growth rate of up to 3%–5%. After 7 days of loading, the rate of prestress loss began to slow down, and the pile-soil contact stress gradually reached a stable state. By 28 days of loading, the prestress loss rate stabilized at 15%–16%, and the fluctuation range of the pile-soil contact stress remained within 2% or less. This phenomenon occurred because the creep effect of the soil continuously reduced the shear strength at the interface, causing the load to gradually transfer from the anchor cables to the anti-slide piles, ultimately achieving a dynamic equilibrium [4].

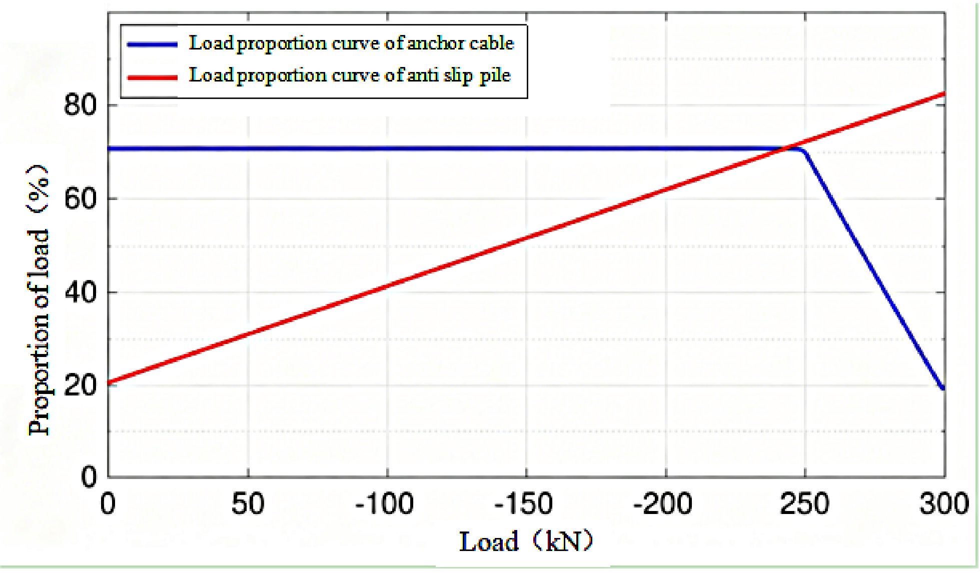

Figure 2. Comparison of load distribution between the anti-sliding pile and the anchor cable

2.3. Establishment of a dynamic load distribution model

Based on experimental data, and through comprehensive consideration of time effects and the shear interaction at the soil-structure interface, a dynamic load distribution model is constructed for the combined reinforcement system of anchor-cable frames and anti-slide piles [5]. The core parameters of this model include the loss rate of anchor cable prestress, pile-soil contact stress, interface shear displacement, and load-holding time. The relationship between load distribution ratio and time is fitted using an exponential function, with the basic model presented as follows.

$$\eta_1(t) = 0.68e^{-0.02t} + 0.32 \tag{1}$$

$$\eta 2(t) = 0.32(1 - e^{-0.02t}) + 0.18 \tag{2}$$

In the formula, $\eta_1(t)$ represents the proportion of load borne by the anchor cable; t represents the load holding time; $\eta 2(t)$ represents the proportion of load borne by the anti-slide pile. Through model validation, it is found that the error between the calculated and experimental values does not exceed 5%, and the goodness of fit can reach 0.96 or above, accurately reflecting the load distribution pattern under different load holding times. After incorporating the time effect factor, the prediction accuracy of the model will be further improved, enabling its use in dynamic prediction of engineering load distribution. In terms of load distribution impact, the greater the interface shear strength, the larger the proportion of load borne by the anchor cable. As the interface shear strength gradually decreases, the load will gradually transfer from the anchor cable to the anti-slide pile, thereby increasing the force on the anti-slide pile [6]. Therefore, during modeling, the interface shear strength and correction coefficient should also be reasonably introduced to further enhance its applicability.

3. Criteria for collaborative design of combined reinforcement with anchor cable frames and anti-slide piles

3.1. Analysis of the impact of soil heterogeneity

To clarify the impact of soil heterogeneity on the collaborative effect of anchor cables and anti-slide piles, this study selected three typical heterogeneous soil types, namely silty clay, sandy loam, and gravelly soil, and conducted experiments on their collaborative reinforcement effects. During the experiments, the basic parameters of the anchor cables and anti-slide piles were kept constant, while only the soil type was altered [7]. Monitoring continued according to the aforementioned plan until the system failed, with a focus on analyzing the impact pattern of soil properties on the collaborative effect. The experiments revealed that the heterogeneous nature of the soil directly affects collaborative failure. Silty clay, with an interface shear strength below 50 kPa, exhibits significant creep effects, causing long-term load deviation towards the anti-slide pile and ultimately leading to its premature failure. Sandy loam, with an interface shear strength between 50–100 kPa, maintains a balanced load distribution between the pile and anchor, allowing the entire system to fail collaboratively. Gravelly soil, with an interface shear strength above 100 kPa, bears most of the load on the anchor cable, which may fail first under long-term effects. Additionally, the stratified nature of the soil exacerbates the imbalance in pile-anchor loading, making local damage more likely.

3.2. Classification of collaborative failure modes

Based on experimental data and the heterogeneous characteristics of the soil, this study primarily classifies the combined reinforcement system of anchor cable frames and anti-slide piles into three collaborative failure modes. The first mode is the premature failure of the anti-slide pile, triggered primarily by soil with high clay content, poor permeability, and significant creep effects. The main manifestations are overall cracking or breaking, with the anchor cable's bearing capacity not reaching its limit, and the system failure being dominated by the anti-slide pile. The second mode is the premature failure of the anchor cable frame, triggered mainly by coarse soil particles, strong permeability, and high interface shear strength. The main manifestations are anchor cable pullout or breakage, with the anti-slide pile's load-bearing role not being fully utilized, and the system failure being dominated by the anchor cable [8]. The third mode is a collaborative failure of both. Triggered by uniform soil properties and moderate interface shear strength, in this mode, the anchor cable and anti-slide pile fail simultaneously under ultimate bearing capacity.

3.3. Proposal of differentiated design criteria

For the three collaborative failure modes mentioned above, during the design process of the combined reinforcement system, designers can propose differentiated design criteria based on key indicators such as actual soil type, interface shear strength, and creep coefficient, combined with specific geological conditions. This will comprehensively clarify the three design directions of strong pile-weak anchor, strong anchor-weak pile, and balanced pile-anchor [9]. This approach ensures that different design plans are well-suited to specific geological conditions, thereby reasonably avoiding the risk of collaborative failure in the combined reinforcement system. The basic criteria and design points are shown in **Table 1**.

Table 1. Key points for differentiated design criteria of combined reinforcement plans for anchor cable frames and anti-slide piles based on different geological conditions

No.	Criterion Indicator	Strong Pile – Weak Anchor	Strong Anchor – Weak Pile	Balanced Pile-Anchor
1	Soil Type	Silty clay	Sandy loam	Gravelly soil
2	Interface Shear Strength (kPa)	< 50	50–100	> 100
3	Creep Coefficient	> 0.03	0.01–0.03	< 0.01
4	Collaborative Failure Mode	Pile fails first	Anchor fails first	Simultaneous pileanchor failure
5	Design Key Points	Appropriately increase the length and crosssection of the antislide pile, enhance the pile strength, reduce the anchor prestress, and reasonably decrease the load transfer from the pile.	Optimize pileanchor parameters, ensure the ratio of anchor prestress to pile bearing capacity > 1 to achieve uniform load distribution.	Select highstrength anchors, appropriately increase anchor prestress and number, moderately reduce the crosssection of the antislide pile, and achieve reasonable cost savings.

4. Long-term prediction of combined reinforcement with anchor cable frames and anti-slide piles

4.1. Fatigue crack propagation test under cyclic loading

To delve into the fatigue crack propagation behavior of anchor cable threads under cyclic loading conditions, this study selected the most representative threaded segment of the anchor cable as the test section. Made of high-strength steel, this segment was 100mm in length and featured a thread specification of M24×3. Fatigue crack propagation tests were conducted using an MTS fatigue testing machine, with a stress ratio set at 0.3, a frequency controlled at 5Hz, and a maximum stress value of 1200MPa, cycling until fracture occurred in the threaded segment of the anchor cable. During the tests, the fatigue, crack initiation, and propagation processes of the threaded segment were observed in real-time using a microscope. Based on the observations, the relationships between crack length, propagation rate, and the number of cycles were recorded. Additionally, the specific stress distribution within the threaded segment was monitored. To clarify the impact of surface treatments on fatigue performance, this study conducted tests on four groups of threaded segments with different surface treatments: untreated, chrome-plated, zinc-plated, and shot-peened. Three specimens were tested for each group, and the average values were taken as the final test results for subsequent analysis, ensuring more reliable outcomes.

4.2. Analysis of fatigue crack propagation behavior

The tests revealed that, under cyclic loading conditions, the fatigue crack propagation characteristics of the anchor cable threaded segment could be divided into three stages. The first stage is crack initiation, occurring between 0–105 cycles, where cracks begin to appear in the stress concentration area at the root of the thread, with a length of 2mm or less and a relatively slow propagation rate of 1×10-7m/cycle or less. The primary factor influencing crack propagation at this stage is stress concentration. The second stage is stable crack propagation, occurring between 105–109 cycles, where the crack length increases to approximately 2.0mm, and the propagation rate remains stable at 1×10-7-5×10-7mm/cycle. Both stress concentration and material fatigue wear play dominant roles in this stage. The third stage is unstable crack propagation, occurring after more than 106 cycles, where the crack length exceeds 2.0mm and exhibits a tendency for rapid propagation, with a propagation rate exceeding 5×10-7mm/cycle, ultimately leading to fracture of the thread. Additionally, the surface treatment method significantly affects the fatigue cracks of anchor cable threads. The tests found that, under shot-peening treatment, the crack initiation time can be extended by 30%–40% compared to the untreated condition, and the propagation rate can be reduced by 25%–30%, resulting in the longest fatigue life. Chrome-plating follows, then zinc-plating, with the untreated segment having the shortest fatigue life. Furthermore, time effect analysis revealed that, after 1–5 years of service, the fatigue performance of the anchor cable threaded segment begins to decline, with crack propagation increasing at an annual rate of 5%–8%, primarily due to environmental corrosion.

4.3. Life prediction model and anti-fatigue optimization measures

Based on the above test data, as well as time effects and fatigue crack propagation behavior, this study constructed the following life prediction model for the anchoring system.

$$N(t) = N_0 \cdot k \cdot e^{-0.07t} \tag{3}$$

Among them, $N(t)$ represents the fatigue life of the threaded section after years of service; N_0 represents the initial life; k represents the correction factor for thread surface treatment; and t represents the years of service. Verification shows that the error of this model is below 4%, with a goodness of fit reaching 97% or higher, indicating high prediction accuracy. Based on the prediction results of this model, in the design of combined reinforcement, designers can adopt the measures shown in **Table 2** to optimize the threaded section of anchor cables, thereby further extending their fatigue life and ensuring the long-term durability of the combined reinforcement structure [10].

Table 2. Optimization measures for fatigue resistance of anchor cable threads

No.	Optimization Measure	Main Function	Fatigue Life Extension
1	Shot peening of threaded section	Reduce stress concentration	30%–40%
2	Optimization of anti-corrosion coating	Improve anti-corrosion performance	20%–25%
3	Optimization of thread parameters	Reduce stress concentration	15%–20%

5. Conclusion

In summary, this paper takes the dynamic analysis of pile-soil contact stress as its foundation to analyze the load transfer law under the combined reinforcement state of anchor cable frames and anti-slide piles. Through experimental methods, it clarifies the dynamic load transfer law, reveals the main collaborative failure modes and fatigue characteristics of anchor cables, and proposes targeted optimization measures. This effectively addresses the challenges associated with the combined reinforcement of these two elements, providing scientific and technical references for subsequent applications in related engineering projects.

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Disclosure statement

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