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TENSILE UPLIFT CAPACITY AND FAILURE MECHANISMS OF SCREW-PILE ANCHORS IN CLAY SOIL UNDER REPEATED LOADING

KAPASITAS ANGKAT TARIK DAN MEKANISME KEGAGALAN ANCHOR TIANG ULIR DALAM TANAH LIAT DI BAWAH PEMBEBANAN BERULANG

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Abstract

This study investigates the tensile uplift capacity of screw piles in clay soil as an alternative anchoring system for slope stabilization in cohesive ground conditions. The research aims to address the limited availability of empirical field data on screw-pile behavior under repeated loading and to evaluate the agreement between theoretical predictions and actual in situ responses. The methodology employs an experimental approach through in situ testing with screw-pile diameters of 10 cm, 15 cm, and 20 cm, and embedment depths ranging from 0.6 m to 1.0 m. The tests were conducted under both static and repeated tensile loading using a hydraulic jack system, accompanied by vertical deformation measurements to establish load–displacement curves. Theoretical capacity was calculated using a limit equilibrium approach for comparison with experimental results. The findings reveal a nonlinear load–displacement response, characterized by initial stiffness followed by progressive deformation into the post-yield stage. At a maximum load of 2.858 tons, deformation increased with diameter, from 5.10 cm (10 cm) to 8.49 cm (20 cm). Under repeated loading, failure occurred at a lower load of approximately 1.6 tons with a maximum deformation of 1.648 cm, indicating potential capacity degradation due to cyclic loading. The comparison between theoretical and field results shows significant deviations, with analytical predictions generally underestimating the in situ capacity. This highlights the limitations of simplified models that do not fully account for shaft adhesion, installation disturbance, soil heterogeneity, pore-water pressure effects, and cyclic degradation. Overall, this study contributes valuable field pull-out test data for screw piles in clay under repeated loading, emphasizing the need for design calibration based on full-scale testing for slope stabilization applications. The results also suggest opportunities for further research involving long-term monitoring and advanced modeling of cyclic degradation.

Keywords : screw pile, tensile uplift capacity, clay soil, repeated loading, field testing.

Abstrak

Studi ini menyelidiki kapasitas tarik ke atas tiang sekrup dalam tanah lempung sebagai sistem penjangkaran alternatif untuk stabilisasi lereng dalam kondisi tanah kohesif. Penelitian ini bertujuan untuk mengatasi keterbatasan ketersediaan data empiris lapangan mengenai perilaku tiang ulir di bawah beban berulang dan untuk mengevaluasi kesesuaian antara prediksi teoretis dan respons aktual di lapangan. Metodologi ini menggunakan pendekatan eksperimental melalui pengujian di lokasi dengan diameter tiang ulir 10 cm, 15 cm, dan 20 cm, serta kedalaman penanaman mulai dari 0,6 m hingga 1,0 m. Pengujian dilakukan di bawah beban tarik statis dan berulang menggunakan sistem dongkrak hidrolik, disertai pengukuran deformasi vertikal untuk membuat kurva beban-perpindahan. Kapasitas teoretis dihitung menggunakan pendekatan kesetimbangan batas untuk dibandingkan dengan hasil eksperimen. Temuan tersebut mengungkapkan respons beban-perpindahan yang tidak linier, ditandai dengan kekakuan awal diikuti oleh deformasi progresif ke tahap pasca-luluh. Pada beban maksimum 2.858 ton, deformasi meningkat seiring dengan diameter, dari 5.10 cm (10 cm) menjadi 8.49 cm (20 cm). Di bawah pembebanan berulang, kegagalan terjadi pada beban yang lebih rendah yaitu sekitar 1,6 ton dengan deformasi maksimum 1,648 cm, menunjukkan potensi penurunan kapasitas akibat pembebanan siklik. Perbandingan antara hasil teoritis dan lapangan menunjukkan penyimpangan yang signifikan, dengan prediksi analitis umumnya meremehkan kapasitas in situ. Hal ini menyoroti keterbatasan model yang disederhanakan yang tidak sepenuhnya memperhitungkan adhesi poros, gangguan pemasangan, heterogenitas tanah, efek tekanan air pori, dan degradasi siklik. Secara keseluruhan, penelitian ini memberikan data uji tarik lapangan yang berharga untuk tiang sekrup dalam tanah liat di bawah beban berulang, menekankan perlunya kalibrasi desain berdasarkan pengujian skala penuh untuk aplikasi stabilisasi lereng. Hasilnya juga menunjukkan peluang untuk penelitian lebih lanjut yang melibatkan pemantauan jangka panjang dan pemodelan canggih degradasi siklik..

Kata Kunci : tiang sekrup, kapasitas angkat tarik, tanah lempung, pembebanan berulang, pengujian lapangan.

1. INTRODUCTION

Slope stability is one of the fundamental issues in geotechnical engineering, as slope failures can cause substantial losses in terms of human safety and infrastructure damage. Natural and man-made slopes are often disturbed by changes in soil stress conditions, increased pore-water pressure, and human activities such as road construction, slope cutting, and land-use change. These factors lead to an increase in shear stress that may eventually exceed the shear strength of the soil, triggering landslides. Therefore, the need for effective and sustainable slope stabilization methods is highly important in the context of infrastructure development in regions dominated by cohesive soils.

Various slope stabilization approaches have been developed in geotechnical practice, ranging from surface reinforcement to deep retaining systems. In recent decades, stabilization methods based on combinations of structural elements and anchoring systems have demonstrated superior performance, particularly in cohesive soils. Pile–anchor frames, prestressed tiebacks with antislide piles, anchored geosynthetics, and hybrid granular/stone column–anchor systems have been proven to mobilize deep passive resistance and provide deformation control through active prestressing. This has been supported by centrifuge, numerical, and laboratory studies confirming the effectiveness of such combined systems in reducing slope deformation (Xue et al., 2024; Du et al., 2023; Wu et al., 2021; Zhang et al., 2023; Phanikumar et al., 2008).

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Nevertheless, the main challenge in slope stabilization lies not only in selecting an appropriate reinforcement system but also in the uncertainty of anchor capacity under field conditions, particularly in clay soils. Cohesive soils exhibit complex characteristics such as plastic behavior, sensitivity to moisture variation, and a tendency for long-term deformation. Under these conditions, anchoring systems must effectively transfer tensile loads through adhesion and soil resistance mechanisms around the anchor element. Inaccurate estimation of tensile capacity may result in design failure or excessive deformation that threatens slope stability.

In general, widely adopted solutions include conventional anchoring systems such as inclined anchors, plate anchors, under-reamed anchors, suction anchors, and granular pile anchors. These systems have been extensively studied through numerical and laboratory approaches, as well as several field case studies in clay soils (Golait et al., 2017; Du et al., 2014; Phanikumar et al., 2008). However, most existing research emphasizes theoretical models or simulations, while long-term empirical evidence from field testing remains limited.

Several specific solutions have been developed in the scientific literature to enhance anchoring effectiveness in cohesive soils. Studies indicate that pile–anchor combinations with prestressing systems can significantly increase resistance capacity and reduce slope deformation (Zhao et al., 2014; Du et al., 2023). Anchored geosynthetics also offer advantages in distributing tensile forces more evenly in shallow zones, while hybrid granular column–anchor systems can improve drainage as well as soil resistance capacity (Wu et al., 2021; Zhang et al., 2023). These solutions highlight that effective anchoring systems must comprehensively account for soil–structure interaction.

However, advances in slope reinforcement technology have led to the use of screw/helical anchors or screw piles as modern anchoring alternatives. These systems offer relatively rapid installation and the ability to mobilize resistance through helix plates. Unfortunately, the available literature remains very limited in providing explicit field studies on the tensile capacity of screw/helical anchors in clay soils. The absence of long-term in situ pull-out data for screw pile systems indicates a clear research gap, particularly in the context of slope stabilization design in cohesive ground (Hamasaki et al., 2016).

In addition to limited field data, repeated or cyclic loading is another critical issue that has not been fully resolved. Numerical and laboratory studies suggest that cyclic loading, creep processes, and environmental degradation can reduce pull-out resistance and cause prestress loss over time. Cyclic degradation, prestress loss, and corrosion or deterioration of anchor elements may decrease the long-term capacity of slope stabilization systems, and therefore must be considered in design (Hu & Gao, 2014; Gao et al., 2022; Hamasaki et al., 2016; Maming et al., 2021). However, long-term field data regarding cyclic loading effects in cohesive soils remain scarce, reinforcing the need for directly monitored field testing (Hamasaki et al., 2016).

Based on this overview, previous studies have provided a strong foundation on anchoring systems and pile–anchor combinations for slope stabilization. Nevertheless, research has

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largely focused on conventional anchors and numerical or laboratory approaches. Field investigations of the tensile capacity of screw/helical anchors in clay soils, particularly under repeated loading conditions, are still insufficient. This gap creates an urgent need for empirical in situ data to validate theoretical models and refine design guidelines.

Therefore, this study aims to evaluate the tensile uplift capacity of screw piles in clay soil through field testing under repeated loading. The study emphasizes the influence of diameter and embedment depth variations on load–displacement response and failure mechanisms. The novelty of this research lies in providing in situ pull-out test data for screw piles in cohesive soils under cyclic loading conditions, which has rarely been reported in the literature. The scope of the study is limited to clay soil with specific screw configurations, and the results are expected to contribute scientifically and practically to the future development of slope stabilization systems based on screw/helical anchors.

Figure 1. Tensile pull-out testing of screw-pile anchors

2. RESEARCH METHOD

This research was designed as an experimental study based on field (in situ) testing to evaluate the tensile uplift capacity of a screw-pile system installed in clay soil, as illustrated in Figures 1 and 2. The primary focus of the study is to understand the load–deformation response under repeated tensile loading conditions and to identify the failure mechanisms occurring in the anchor element.

The tests were conducted in clay soil with predominantly cohesive conditions, which is a common soil type in many landslide-prone slope areas. Clay was selected due to its plastic behavior, sensitivity to changes in moisture content, and tendency for long-term deformation. The key soil parameters relevant to anchor capacity analysis include undrained cohesion and the effective stress conditions surrounding the pile element. In anchor design for cohesive soils, the contribution of shaft adhesion and the bearing capacity of the helix tip are the primary factors governing tensile resistance (Stanier et al., 2014; Lutenegger, 2011).

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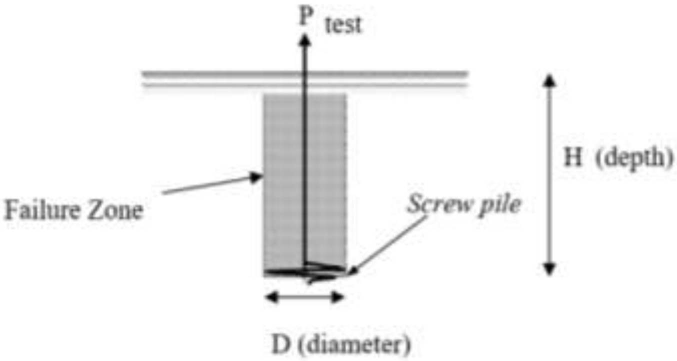
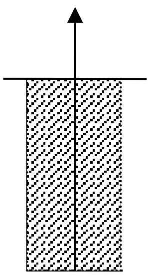


Figure 2. Schematic diagram of the tensile pull-out test of screw-pile anchors

Table 1. Test types, parameters, and treatment conditions of the specimens

Soil Type	**Soil Density (t/m^3) / Water Content (%)**	**Screw Configuration (n)**	**Model & Diameter *Screw***			**Number of Specimens**	**Note**
			A 10 (cm)	B 15 (cm)	C 20 (cm)		
CLAY	$\gamma_d L_1 / W_1$	2	2	2	2	6	
P 	$\gamma_d L_2 / W_2$	2	2	2	2	6	
	$\gamma_d L_3 / W_3$	2	2	2	2	6	
	$\gamma_d L_4 / W_4$	3	-	2	-	2	*By Failure Plane*

a. Screw-Pile Specifications and Configuration Variations

The screw-pile elements used in this study were designed with geometric variations to evaluate the influence of diameter and embedment depth on tensile capacity, as presented in Table 1. The tested diameters were 10 cm, 15 cm, and 20 cm, while the embedment depths ranged from 0.6 m to 0.8 m and 1.0 m. A total of 20 specimens were prepared with different screw configurations, including systems with helix numbers of n = 2 and n = 3 under the by failure plane collapse condition. These variations were intended to examine the principle that tensile capacity increases with larger helix bearing area and greater effective embedment depth until reaching diminishing returns (Salem & Hussein, 2017; Yuan et al., 2024). In the literature, the uplift capacity of screw piles is strongly influenced by helix diameter, the number of helices, and helix spacing, which together determine the mobilized soil volume (Stanier et al.,

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2014). Therefore, the geometric variations applied in this research aim to produce a field dataset that can be compared with these theoretical trends.

The installation of the screw piles was carried out manually at the test site, ensuring that the penetration depth matched the design specifications. This manual installation reflects practical field conditions, although it may also introduce variability in installation quality. In modern practice, screw pile installation is often accompanied by installation torque recording to correlate installation behavior with the ultimate tensile capacity (Lin et al., 2022). However, in this study, torque measurements were not fully instrumented, and thus the test results primarily emphasize the actual load–deformation response.

b. Cyclic Uplift Testing Method

The main test conducted in this study was a field pull-out test under repeated loading conditions. This method follows the common in situ anchor testing approach known as a full-scale static uplift test, which can be performed under either monotonic or cyclic loading (Salem & Hussein, 2017). Tensile loads were applied using a hydraulic jack with a reaction support system. The loading was conducted incrementally until reaching the maximum load or until deformation indicated failure.

Cyclic testing was selected because slope conditions in the field are often subjected to dynamic or repeated loading due to traffic-induced vibrations, seasonal pore-water pressure variations, and creep processes. Previous studies have shown that cyclic loading can reduce pull-out resistance and cause long-term prestress loss (Hu & Gao, 2014; Hao et al., 2022; Wang et al., 2023). However, field-based cyclic data in clay soils remain limited, making this testing program an important contribution to anchor research in cohesive ground conditions.

During the tests, the primary parameters measured were the applied tensile load and the vertical deformation of the pile. In standard practice, field tests commonly employ load cells, strain gauges, and displacement transducers to obtain high-precision data (Yuan et al., 2024; Lin et al., 2022). In this study, deformation was recorded as displacement changes over the loading duration, allowing load–deformation curves to be established for each diameter and embedment depth variation.

3. RESULT AND DISCUSSION

The field test results indicate that the screw piles installed in clay soil exhibited a nonlinear load–deformation response. The general pattern of the observed uplift curves includes an initial stiffness stage, followed by progressive deformation toward yielding, and subsequently a large-displacement tail where the load increase becomes relatively small (Figure 3). This behavior is consistent with the performance of helical/screw piles in saturated clay, which is governed by a combination of helix bearing capacity and shaft adhesion (Stanier et al., 2014; Lutenegger, 2011). In general, failure in such systems is associated with the formation of a near-cylindrical failure surface that mobilizes the bearing resistance of the largest helix along with the adhesion contribution along the shaft between helices.

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In this study, the recorded maximum deformation increased with increasing screw-pile diameter, while the maximum tensile capacity showed trends influenced by geometric configuration and failure plane conditions. These results provide an empirical basis for evaluating the capacity of screw-pile anchors as a slope stabilization system in cohesive soils.

Figure 3. Observed failure mode of screw-pile anchors during the field tensile pull-out test, showing the development of the failure surface and associated deformation pattern

c. Maximum Tensile Capacity Based on Diameter Variations

The tests were conducted on three main diameter variations, namely 10 cm, 15 cm, and 20 cm (Table 2). Field results indicate that under the maximum applied load of 2.858 tons, the resulting deformation differed significantly among the diameters. For the 10 cm diameter, the maximum deformation was recorded at 5.10 cm. For the 15 cm diameter, deformation increased to 6.88 cm, while for the 20 cm diameter, deformation reached 8.49 cm. In addition, the by failure plane configuration for the 15 cm diameter exhibited a deformation of 7.30 cm under the same load. These data are summarized in the field test results, demonstrating a direct relationship between increasing diameter and increasing deformation at a given load capacity.

Table 2. Tensile pull-out test results of screw-pile anchors under static and repeated loading conditions

ϕ Screw-Pile (cm)	P_{max} (ton)	Deformation (cm)
10	2.858	5.10
15	2.858	6.88
20	2.858	8.49
15 (by failure plane)	2.858	7.30

This phenomenon is consistent with findings in the literature that screw piles in saturated clay exhibit nonlinear curves with large post-yield deformations, because mobilization of helix bearing resistance requires relatively large displacement before reaching ultimate conditions (Stanier et al., 2014). Although increasing helix diameter theoretically enhances bearing capacity, it may also induce greater deformation due to the larger volume of mobilized soil.

d. Influence of Failure Plane Configuration and Repeated Loading

One of the main focuses of this study was repeated loading testing under the by failure plane collapse condition. In the cyclic test, failure was reported to occur at a load of approximately 1.6 tons with a maximum deformation of 1.648 cm. These results indicate that repeated loading can lead to failure at lower loads compared with the maximum monotonic capacity, even though the maximum deformation remains relatively small in the early stages.

The literature explains that helical anchor systems exhibit three cyclic loading regimes: cyclic stable, hypo stable, and cyclic degradation. In the degradation regime, deformation accumulates and residual prestress loss occurs, reducing long-term tensile capacity (Guo et al., 2018; Hu & Gao, 2014; Hao et al., 2022; Wang et al., 2023). In the context of this study, failure under lower cyclic loads may be associated with cyclic degradation mechanisms, although long-term data are required to confirm this trend.

However, the literature also notes that in some cases, reloading may increase the shaft contribution due to preshearing or changes in adhesion conditions after reloading, allowing partial recovery of capacity (Salem & Hussein, 2017; Yuan et al., 2024; Lutenegger, 2011). Therefore, the findings of this study further emphasize the importance of evaluating cyclic loading effects in slope anchor design.

e. Field Factors Affecting Test Results

This study also identified several practical factors that may explain discrepancies between theoretical predictions and field performance. These include manual installation, which can produce variations in effective embedment depth, measurement accuracy, deformation reading procedures, and the influence of temperature and vibration on the hydraulic jack system. In addition, heterogeneous field soil conditions may lead to variability in adhesion and resistance mobilization that are not fully captured in theoretical models.

The literature confirms that anchor capacity is strongly influenced by local soil strength, embedment depth, helix number, and installation effects that may disturb the soil structure around the pile (Salem & Hussein, 2017; Yuan et al., 2024). Thus, the results of this study highlight the importance of field-based testing approaches to reduce design uncertainty.

f. Discussion

The results of this study provide empirical insight into the tensile capacity behavior of screw piles in clay soil, particularly under repeated loading conditions. In general, the load–deformation response obtained exhibits nonlinear characteristics consistent with uplift anchor behavior in cohesive soils. During the initial loading stage, the system shows relatively high initial stiffness, followed by a progressive yielding phase leading to large deformations in the post-peak condition. This pattern supports findings in the literature that screw/helical anchors

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in saturated clay are governed by a combination of helix bearing resistance and shaft adhesion, with failure often developing through a plug or cylindrical shear mechanism around the lead helix (Stanier et al., 2014; Nakazawa et al., 2015).

The failure mechanism observed in this study can be interpreted as the mobilization of a near-cylindrical failure surface involving soil surrounding the largest helix. The literature classifies uplift anchor behavior according to embedment ratio into shallow, transition, and deep modes, each influencing failure surface geometry and the contribution of shaft adhesion (Stanier et al., 2014). In the context of this study, variations in embedment depth and helix diameter likely affected the transition between these mechanisms, although the tests were limited to a specific embedment range. The increased deformation recorded for larger diameters can also be explained by the greater mobilized soil volume, requiring larger displacement before helix bearing reaches ultimate capacity.

One of the key aspects discussed is the significant discrepancy between theoretical capacity and field test results. Analytical calculations based on limit equilibrium or plate bearing analogies provided lower capacity estimates compared with the maximum loads recorded in situ. This phenomenon is consistent with the literature emphasizing that simplified analytical models may capture general trends but often diverge from field results because they neglect complex shaft adhesion contributions, installation effects, layered stratigraphy, pore-water pressure influences, and cyclic degradation (Lutenegger, 2011; Salem & Hussein, 2017; Hu & Gao, 2014). In this study, manual screw-pile installation may also have introduced variability in torque and crowd force, affecting soil conditions around the pile and resulting in capacities different from ideal theoretical assumptions.

Furthermore, the repeated loading applied in this study provides important indications regarding cyclic anchor behavior. Failure under cyclic conditions was reported at lower loads than under monotonic conditions, which may be associated with cyclic degradation mechanisms and accumulated deformation. The literature states that screw/helical anchors may experience three cyclic regimes—cyclic stable, hypo stable, and cyclic degradation—where the degradation regime leads to reduced long-term resistance due to prestress loss and changes in soil structure around the helix (Hu & Gao, 2014; Gao et al., 2022; Hamasaki et al., 2016). Thus, these findings reinforce the argument that slope anchor design cannot rely solely on monotonic static capacity but must account for realistic cyclic loading effects under field conditions.

This discussion also highlights the relevance of screw piles as an alternative anchoring system for slope stabilization in cohesive soils. Recent studies show that combined systems such as pile–anchor frames, prestressed tiebacks, anchored geosynthetics, and hybrid granular/stone column–anchor configurations perform best because they mobilize deep passive resistance and control deformation through active prestressing (Zhao et al., 2014; Xue et al., 2024; Du et al., 2023; Wu et al., 2021; Zhang et al., 2023; Phanikumar et al., 2008). However, the literature also indicates that explicit field data on the tensile capacity of screw/helical anchors in clay remain very limited (Hamasaki et al., 2016). Therefore, this study provides an

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initial empirical contribution toward filling this gap, although further testing with full instrumentation is required.

The practical implication of these results is the need for a more comprehensive design hierarchy. The literature recommends that uplift capacity predictions should be based on full-scale monotonic and cyclic field tests with installation torque logging, which can then be used to calibrate torque–capacity correlations and FEM models incorporating shaft/grout contributions and cyclic degradation effects (Yuan et al., 2024; Hambleton & Stanier, 2019; Hamasaki et al., 2016; Gao et al., 2022; Xue et al., 2024; Zhang et al., 2023). In addition, long-term monitoring is necessary to capture deterioration processes, prestress loss, and soil condition changes that may reduce capacity over the service life.

Overall, this study demonstrates that screw piles in clay have significant potential as slope stabilization anchors, but reliable capacity prediction requires field-based calibration and cyclic loading evaluation. The discrepancies between theoretical and experimental results emphasize that conservative design approaches incorporating partial factors and serviceability limit state checks are essential to ensure long-term safety and performance of modern anchor-based slope reinforcement systems.

4. CONCLUSION

This study evaluates the tensile uplift capacity of screw piles in clay soil through field testing under repeated loading conditions. The research was motivated by the need for more effective slope stabilization systems in cohesive soils, as well as a literature gap regarding the limited availability of long-term in situ test data for screw/helical anchors in clay, particularly under cyclic loading conditions. Based on the experimental results and analysis, several key findings can be formulated.

First, the behavior of screw piles in clay soil exhibits a nonlinear load–deformation response, characterized by an initial stiffness stage followed by progressive deformation into the post-yield condition. This pattern is consistent with the uplift anchor mechanism in cohesive soils, governed by mobilization of the largest helix bearing resistance and shaft adhesion. The increase in maximum deformation for larger diameters indicates that mobilizing ultimate capacity requires a greater volume of soil displacement as helix size increases.

Second, variations in diameter and failure plane configuration influence the deformation response and tensile capacity of the system. At a maximum load of 2.858 tons, deformation increased from 5.10 cm (10 cm diameter) to 8.49 cm (20 cm diameter). Under repeated loading, failure occurred at a lower load of approximately 1.6 tons with a maximum deformation of 1.648 cm. These findings confirm that cyclic loading can trigger capacity degradation and accelerate deformation accumulation, meaning that anchor design cannot rely solely on monotonic static capacity.

Overall, this study contributes valuable empirical field pull-out test data for screw piles in clay under repeated loading, enhancing understanding of failure mechanisms and the limitations of theoretical capacity predictions. Further research is recommended to include long-term monitoring, installation torque instrumentation, and cyclic degradation modeling in order to support more accurate slope stabilization design guidelines.

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