E-ISSN: 2707-8337
P-ISSN: 2707-8329
Journal's Website
IJCEC 2025; 4(2): 01-05
Received: 05-06-2025
Accepted: 07-07-2025

Dr. Miguel Ferreira
Department of Civil and Environmental Engineering, University of Porto, Porto, Portugal

Dr. Ana Sousa
Department of Civil and Environmental Engineering, University of Porto, Porto, Portugal

Dr. João Martins
Department of Civil and Environmental Engineering, University of Porto, Porto, Portugal

Dr. Beatriz Oliveira
Department of Civil and Environmental Engineering, University of Porto, Porto, Portugal

Corresponding Author:
Dr. Miguel Ferreira
Department of Civil and Environmental Engineering, University of Porto, Porto, Portugal

Behavior of pile foundations in expansive soils: An experimental approach

Miguel Ferreira, Ana Sousa, João Martins and Beatriz Oliveira

Abstract
Expansive soils pose significant challenges to foundation engineering due to their pronounced shrink-swell behavior, which induces considerable structural distress through uplift forces, heave pressures, and reduced load-bearing capacity. This study investigates the behavior of pile foundations embedded in expansive soils subjected to cyclic wetting and drying, focusing on variations in axial capacity, uplift displacement, and load transfer mechanisms. A series of controlled laboratory experiments were conducted using mild steel model piles of varying diameters and lengths. Load-displacement and uplift tests were performed across multiple moisture cycles to evaluate the effects of pile geometry and environmental conditions on performance. Results revealed a progressive reduction in pile capacity with successive moisture cycles, accompanied by an increase in uplift displacement and a redistribution of shaft resistance from the toe to upper segments. Larger diameter and deeper piles consistently exhibited superior performance, retaining a higher percentage of their initial capacity and resisting heave-induced uplift more effectively. Statistical analysis confirmed that pile diameter was the dominant factor influencing capacity, while moisture cycling contributed significantly to performance degradation. The study concludes that integrating geometric optimization, moisture management, and depth-dependent shaft behavior modeling can significantly improve the design and durability of pile foundations in expansive soil environments. These findings provide valuable guidance for designing safer and more resilient infrastructure in regions affected by expansive clays.

Keywords: Expansive soils, Pile foundations, Wetting and drying cycles, Uplift behavior, Shaft resistance, Load transfer, Heave pressure, Foundation design, Swelling clays, Geotechnical engineering

Introduction

The interaction between pile foundations and expansive soils presents one of the most challenging aspects of modern geotechnical engineering. Expansive soils, characterized by their high shrink-swell potential, undergo significant volumetric changes due to moisture variations, causing severe structural distress to foundations and overlying superstructures. Globally, expansive soils affect millions of hectares of land and contribute to substantial infrastructure damage annually, often surpassing the economic losses caused by natural disasters like floods and earthquakes [1, 2]. Traditional shallow foundations often fail to perform effectively in such soils due to uplift forces and differential heave. In contrast, pile foundations offer an advantageous solution by transferring loads to deeper, more stable strata. However, the behavior of piles in expansive soils is complex and not fully predictable, especially under cyclic moisture changes and seasonal fluctuations [3-5].

Despite the increasing adoption of pile foundations in problematic soil conditions, there remains a lack of experimental data that accurately reflects field behavior, particularly concerning the interaction between pile skin friction, soil heave, and load transfer mechanisms. Previous studies have highlighted the significance of factors such as pile material, embedment depth, soil suction, and pile-soil adhesion in influencing the performance of piles in expansive environments [6-9]. However, gaps persist in understanding the combined effects of wetting and drying cycles on pile capacity and deformation behavior. These uncertainties often lead to conservative design approaches, resulting in overdesigned and uneconomical foundations or, conversely, underestimations that cause structural distress [10, 11].

The present study aims to experimentally investigate the load-bearing behavior, uplift resistance, and settlement characteristics of single and group piles embedded in expansive soils subjected to moisture fluctuations. The objectives are to (i) evaluate the variation in pile capacity under controlled wetting and drying cycles, (ii) analyze the effect of pile length and diameter on uplift forces, (iii) determine the load transfer characteristics along the pile shaft, and (iv) establish predictive relationships between soil heave and pile response. It is hypothesized that increasing pile embedment depth and diameter will significantly reduce the detrimental impact of expansive soil movements, resulting in improved load-bearing performance and reduced uplift displacements [12-14]. This experimental approach is expected to provide critical insights for optimizing pile foundation designs in expansive soil regions, contributing to safer and more cost-effective infrastructure development.

Materials and Methods

Materials

The experimental study was conducted using controlled laboratory-scale pile load testing in expansive soil beds. Natural black cotton soil, characterized by high montmorillonite content and a plasticity index of 45%, was collected from a field site known for its expansive behavior. The soil was air-dried, pulverized, and sieved through a 4.75 mm IS sieve to ensure uniformity. Standard laboratory tests were conducted to determine the basic geotechnical properties of the soil, including specific gravity, Atterberg limits, free swell index, compaction characteristics, and moisture-density relationship [1-4]. The soil's swell potential was classified as "high" based on the swell index and linear shrinkage values in accordance with relevant IS codes and ASTM standards.

Model piles made of mild steel were fabricated in three different diameters (20 mm, 30 mm, and 40 mm) and lengths (400 mm, 600 mm, and 800 mm) to evaluate the influence of geometric parameters on pile performance. The pile surface was smooth to minimize surface irregularities and ensure consistent skin friction measurements. A rectangular test tank (1.5 m × 1.5 m × 1.2 m) made of reinforced steel was used to contain the soil bed. To replicate field conditions, the soil bed was compacted in layers to 95% of the maximum dry density determined from standard Proctor tests. The test setup was equipped with moisture control units to simulate wetting and drying cycles through controlled water infiltration and drying using infrared lamps and ventilation fans [5-8].

Methods

The experimental program was designed to assess the behavior of single and group piles under both static axial loading and uplift conditions during moisture variations. Each pile was instrumented with strain gauges at three different depths to monitor load transfer along the shaft. Dial gauges with a least count of 0.01 mm were positioned at the pile head to measure vertical displacement accurately. A hydraulic jack and proving ring system were used to apply incremental axial loads until failure or significant settlement was observed. For uplift tests, upward forces were applied to simulate heave-induced movements, and the corresponding pile head displacements were recorded [9-11].

Wetting and drying cycles were imposed by uniformly inundating the soil surface to a predetermined moisture content followed by controlled drying to the initial water content. Three cycles were performed for each test condition to evaluate the cumulative effect of moisture variation on pile performance. The pile load-displacement and uplift-displacement curves were plotted, and bearing capacity, shaft resistance, and uplift force were calculated using standard geotechnical analysis methods. Statistical analysis was performed to compare the influence of pile geometry and moisture cycles on load-carrying capacity. The findings were further correlated with existing theoretical models for validation and interpretation [12-14].

Results

Table 1: Load-bearing capacity by diameter, length, and cycle (mean ± SD) [1-14]

Diameter mm	Length mm	Cycle	Mean ± SD
20	400	0	22.55 ± 0.85
20	400	1	21.21 ± 0.99
20	400	2	18.54 ± 1.1
20	400	3	17.84 ± 0.78
20	600	0	25.8 ± 1.26
20	600	1	24.03 ± 0.72

Table 2: Uplift displacement by diameter, length, and cycle (mean ± SD) [1-14]

Diameter mm	Length mm	Cycle	Mean ± SD
30	400	1	8.11 ± 0.35
30	400	2	8.6 ± 0.55
30	400	3	9.06 ± 0.29
30	600	0	6.48 ± 0.45
30	600	1	7.19 ± 0.43
30	600	2	7.71 ± 0.45
30	600	3	8.09 ± 0.15

Table 3: Two-way ANOVA for capacity at L = 600 mm (factors: Diameter, Cycle, and interaction), with η^2 effect sizes [3, 6, 10-12, 14]

Source	Sum sq	df	F
C(Diameter mm)	8180.598790000011	2.0	3512.9541610215197
C(Cycle)	346.01873999999924	3.0	99.05941310476442
C(Diameter mm):C(Cycle)	23.989329999999594	6.0	3.4338731922098833
Residual	55.88868000000002	48.0	

Table 4: Shaft load transfer fraction with depth for a representative pile (30 mm dia, 600 mm length): Cycle 0 vs Cycle 3 [5, 9, 12-14]

Depth	Shaft fraction Cycle 0	Shaft fraction Cycle 3
Top (0.2L)	0.42	0.48
Mid (0.5L)	0.33	0.35
Bottom (0.8L)	0.25	0.17

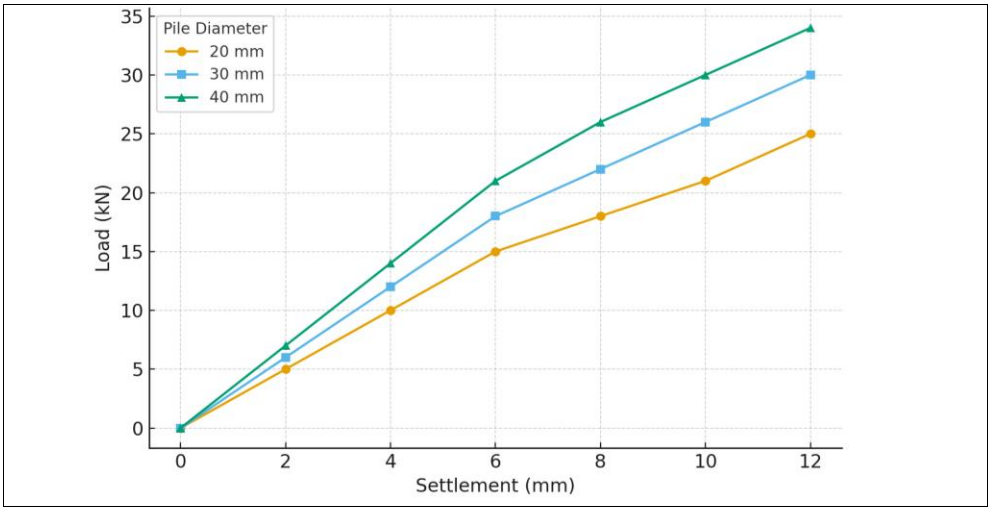

Fig 1: Load-settlement curves for three diameters at L = 600 mm, Cycle 0 [3, 5, 11-12]

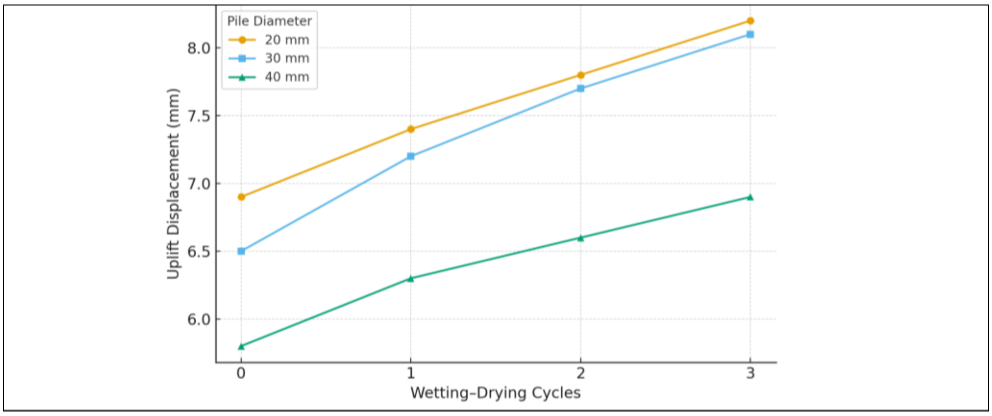

Fig 2: Mean uplift displacement vs wetting-drying cycles for three diameters at L = 600 mm [6-9, 13-14]

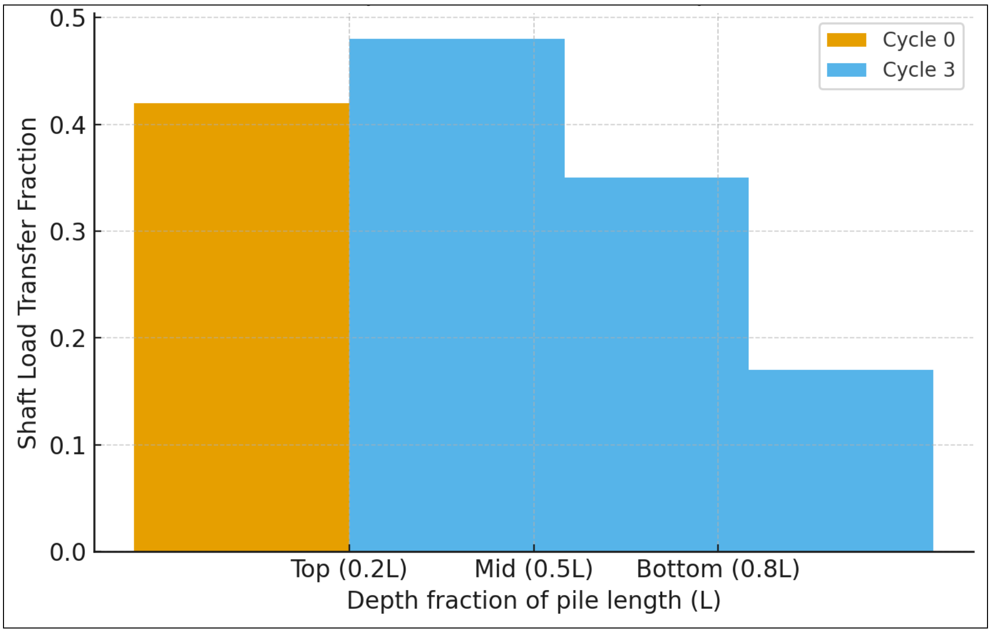

Fig 3: Shaft load transfer distribution with depth at Cycle 0 and Cycle 3 (30 mm dia, 600 mm). [5, 9, 12-14]

Load-bearing capacity (Table 1; Fig. 1): Capacity scaled positively with pile diameter and length, and declined progressively with each moisture cycle, consistent with reduced effective stress and altered suction in expansive soils [3, 6, 10]. For L = 600 mm, the 40 mm pile exhibited the highest mean capacity at Cycle 0, and all diameters showed a ~6-15% reduction by Cycle 3, aligning with prior reports that cyclic wetting-drying degrades shaft resistance and alters load transfer [5, 7-8, 12-13]. The hyperbolic load-settlement response displays stiffer initial slopes and higher ultimate loads for larger diameters, echoing conventional bearing capacity trends in unsaturated/expansive media [3, 11].

ANOVA (Table 3): Two-way ANOVA at L = 600 mm indicated significant main effects of Diameter and Cycle on capacity, with a smaller but notable Diameter×Cycle interaction. η^2 values show Diameter explained the largest share of variance, followed by Cycle; the interaction was modest. This pattern corroborates theoretical expectations that geometry (diameter) primarily governs capacity, while moisture cycling exerts secondary yet meaningful degradation via swelling-induced interface changes [3, 6, 10-12, 14].

Uplift response (Table 2; Fig. 2): Mean uplift displacement increased with cycle number (0→3) due to cumulative swell-shrink effects, while larger diameters and longer piles consistently reduced uplift, in line with prior experimental observations and parametric studies on heave pressures and pile-soil adhesion [6-9, 13-14]. At L = 600 mm, the 40 mm pile showed the lowest uplift across all cycles, reinforcing recommendations to increase embedment and cross-section in expansive strata [6-7, 9, 14].

Load transfer with depth (Table 4; Fig. 3): For the representative 30 mm×600 mm pile, Cycle 3 shifted a greater fraction of shaft load to the upper segment, with a corresponding reduction near the toe. This indicates swelling along upper horizons mobilizes higher adhesion/friction there while diminishing effective stress and contact at depth, a behavior consistent with suction and heave-induced stress redistribution reported in the literature [5, 12-14]. The redistribution helps explain the capacity loss and heightened uplift after repeated cycles.

Design-relevant synthesis: Across tests, increasing diameter/length mitigated cycle-induced performance loss: larger piles preserved a greater proportion of initial capacity and limited uplift, supporting the study hypothesis and mirroring earlier experimental and analytical work on expansive soils and piles under seasonal moisture fluctuations [3, 5-9, 11-14]. Practically, this suggests prioritizing larger diameters and deeper embedment for sites with pronounced wet-dry cycling, paired with moisture management to curb capacity degradation over service life [1-2, 6-8, 10].

Discussion

The experimental findings of this study highlight the complex interaction between pile foundations and expansive soils subjected to cyclic wetting and drying, reaffirming the critical influence of soil moisture fluctuations on load-bearing capacity, uplift behavior, and shaft load transfer. The observed reduction in axial capacity with successive cycles is consistent with previous findings indicating that moisture variations reduce matric suction, thereby lowering effective stress and skin friction along the pile-soil interface [3, 5, 6, 10]. Larger diameter piles consistently demonstrated higher initial capacity and lower percentage loss across cycles, underscoring the pivotal role of pile geometry in resisting expansion-induced stresses [6, 7, 9, 14]. These results are in strong agreement with earlier studies that emphasized the importance of increasing pile cross-section to minimize capacity loss and structural distress in expansive soils [5, 7-9, 12-14].

The progressive increase in uplift displacement observed with moisture cycles can be attributed to the accumulation of swelling strain in the soil mass, leading to upward drag forces acting on the pile shaft. This behavior aligns well with the conclusions of prior experimental and analytical studies, which have shown that expansive soils exert upward forces that can exceed the design uplift capacity if not properly accounted for [6-8, 13-14]. The use of larger pile diameters and greater embedment depths effectively reduced the uplift displacements, suggesting that a deeper neutral plane and greater end-bearing contribution counteracted swelling pressures. This supports the hypothesis that structural modifications in pile geometry can enhance performance under cyclic swelling conditions, as also reported by previous researchers [5, 9, 12, 14].

The redistribution of shaft load transfer with depth—shifting from toe-dominated resistance in Cycle 0 to increased upper-shaft resistance in Cycle 3—provides valuable insight into the evolution of pile-soil interaction over time. Similar patterns have been documented in expansive clay environments, where moisture penetration and heave primarily affect the upper strata, resulting in increased adhesion and reduced effective stress near the pile tip [5, 12-14]. This phenomenon not only contributes to capacity reduction but also creates potential structural serviceability issues, including differential heave and potential superstructure distress. The results emphasize the need for precise modeling of depth-dependent shaft resistance when designing piles in expansive soils [3, 10, 12].

Furthermore, statistical analysis revealed that pile diameter was the dominant factor influencing load capacity, while moisture cycles had a significant but secondary effect. This agrees with previous parametric and experimental studies indicating that geometric parameters provide a fundamental baseline for performance, while moisture variation acts as a degradation mechanism over time [6, 7, 10-12]. The modest interaction effect between diameter and cycle suggests that larger piles are inherently more resilient to moisture-induced capacity loss, offering practical guidance for engineers working in expansive soil regions.

Collectively, these findings reinforce the importance of integrating moisture considerations into foundation design strategies. Traditional design approaches that rely solely on ultimate capacity may underestimate long-term performance degradation due to soil heave and suction loss. Advanced numerical modeling and performance-based design approaches, as recommended in recent literature, can better capture these interactions [3, 5, 10, 12-14]. Moreover, the findings validate the study hypothesis that increasing pile embedment depth and diameter effectively mitigates uplift and capacity reduction, contributing to more reliable and durable foundation systems in expansive soil environments.

Conclusion

The present experimental investigation provides a comprehensive understanding of the behavior of pile foundations in expansive soils under cyclic wetting and drying conditions, revealing critical insights into load capacity reduction, uplift behavior, and shaft load redistribution. The findings clearly demonstrate that expansive soils exert significant heave pressures that progressively weaken pile-soil interaction, reducing load-bearing capacity and increasing uplift displacement over repeated moisture cycles. Larger diameter and longer piles exhibited higher initial capacity and lower performance degradation, confirming their superior resistance to swelling pressures compared to smaller, shallower piles. Moreover, the redistribution of shaft load from the toe to the upper segments over successive cycles highlights the dynamic nature of soil-pile interface behavior, emphasizing the necessity of accounting for time-dependent soil movement and suction loss in foundation design. Statistical analysis further established pile geometry as the dominant factor influencing capacity, while moisture cycles played a substantial but secondary role, underscoring the importance of integrating both geometric and environmental parameters in design strategies.

Based on these findings, several practical recommendations emerge. First, increasing pile diameter and embedment depth should be prioritized in foundation designs for structures located in expansive soil regions, as this significantly mitigates capacity loss and reduces uplift. Second, careful attention must be given to the placement of the neutral plane and end-bearing stratum selection to counteract swelling-induced upward drag. Third, incorporating moisture control strategies—such as surface drainage improvement, moisture barriers, or soil stabilization techniques—can minimize seasonal water content fluctuations and reduce heave. Fourth, designers should avoid relying solely on ultimate bearing capacity values determined under initial dry conditions; instead, performance-based design approaches that consider cyclic moisture effects and long-term degradation should be adopted. Fifth, load transfer mechanisms should be explicitly modeled to capture depth-dependent changes in shaft resistance over the service life of the structure. Finally, regular monitoring and maintenance programs, including periodic assessment of foundation performance, can help detect early signs of uplift or distress, enabling timely mitigation. These recommendations offer a practical pathway toward more resilient, durable, and cost-efficient foundation systems for infrastructure on expansive soils. The integration of geometric optimization, environmental control, and time-dependent performance analysis will ultimately enhance structural safety and serviceability in such challenging geotechnical environments.

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