Soil subsidence around the pile under lateral cyclic loading in granular soil

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ABSTRACT

In many structures, such as offshore wind turbines, single piles are used in the foundation. These structures are subjected to cyclic loads such as wind and waves. The cyclic load applied to the foundation causes a convective flow of soil around the pile and also to appear subsidence around the pile. The geometry of soil subsidence is influenced by loading frequency, pile embedded length, and soil density. The amount of subsidence based on the number of cycles around the pile, the impact of cyclic loads on the pile's bearing capacity, and variations in loading frequency on the subsidence around the pile have consistently been topics of interest among researchers. To address this question, an experimental program was designed to provide answers. In this research, piles with different embedded lengths have been subjected to one-way cyclic loading. Cyclic tests have been performed with three various frequencies in loose and dense sandy soil. The results of the tests indicate that the depth and radius of the soil subsidence around the pile are various, according to the embedded length of the pile, loading frequency, and soil density. Based on past research and laboratory data, a relationship to estimate soil subsidence depth has been provided and the constant coefficients of this equation have been determined and calibrated. As a result, it is possible to predict the amount of soil subsidence around the pile in each cycle by using this relationship. Also, the results of static loading of the pile before and after applying cyclic loading show that the bearing capacity of the pile may increase or decrease, depending on the soil density in the initial state and the redistribution of soil particles after cyclic loading. In addition, the loading frequency has no considerable effect on the static bearing capacity after cyclic loading.

KEYWORDS

Pile, cyclic loading, frequency, sandy soil, static bearing capacity.

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1. Introduction

In recent decades, wind turbine construction has increased globally due to growing demand for renewable energy, with monopiles being the dominant foundation type making up 79% of offshore installations in Europe [1].

While much research has examined soil–pile interaction under lateral cyclic loading [2, 3], fewer studies have addressed the subsidence of surrounding soil. Experimental and field evidence show that such loading can trigger convective motion of soil particles around the pile, resulting in time-dependent subsidence [4]. This may reduce, have no effect on, or even improve pile bearing capacity [5], while increasing deformation, depending on initial conditions and loading characteristics [6, 7].

This convective movement termed *ratcheting* creates voids at the pile–soil interface, allowing sand migration and local densification [8]. Particle flow is typically more intense behind the pile, causing asymmetric subsidence [9]. As shown in Figure 1, this affected zone can extend up to 1.5 pile diameters laterally and vertically. Two phases characterize the process: initial densification with subsidence and increased resistance, followed by a convective phase with reduced subsidence and stiffness gain, driven by redistribution of shear stress toward weaker zones [10].

Figure 1. Convective movement of sand particles around the pile [9].

This study investigates the effects of loading frequency and pile embedment depth in dense and loose sands on subsidence and static bearing capacity. Cyclic one-way loading was applied at three frequencies to piles with varying embedment. Additionally, by reformulating time-based subsidence models using the number of cycles as the main variable, a more practical predictive approach is proposed.

2. Materials and Method

Wind turbine foundations are installed in various soils, from compacted sands to stiff clays and rocks. For instance, the North Sea soil layers are sandy[11]. This study focuses on sand-pile interaction, similar to previous research [12]. The soil used is Firouzkooh sand, classified as poorly graded sand (SP).

A PVC pipe with a diameter of 63 mm and embedded lengths of 400 mm, 600 mm, and 800 mm was used as the pile. Length-to-diameter ratios between 6 and 13 were chosen to represent both rigid and flexible piles.

The laboratory setup consists of a loading system, soil container, rainfall apparatus, and data recording system (Figure 4). The pile is subjected to cyclic lateral loading using a motor-controlled system and load cell. The loading frequency used in this study is between 0.07 Hz and 0.28 Hz, in line with typical loading frequencies for wind turbine foundations [13].

The soil container was filled layer by layer with sand, maintaining the pile's verticality. After installation, cyclic loading was applied, and displacement sensors measured lateral movement and soil settlement. Loading ratios of 0.4 ($\xi_b = 0.4$) and 0 ($\xi_c = 0.4$) were used for 5000 cycles at three different frequencies. Static tests were conducted to determine the pile's bearing capacity before cyclic tests.

To minimize scale effects, the experimental parameters followed dimensional analysis, with a scale ratio of 1:60.

A key limitation of this study is the exclusion of water, which would affect sand behavior by altering pore pressure during cyclic loading. While dry sand tests may offer results similar to saturated sand tests, water flushing effects and particle mobility would likely complicate the results [14].

3. Results and Discussion

This study investigates the subsidence behavior around piles embedded in loose and dense sand subjected to cyclic lateral loading at three different frequencies (0.07 Hz, 0.14 Hz, and 0.28 Hz) and varying embedment depths.

Subsidence increases with greater pile embedment depth due to higher applied loads. Increasing the loading frequency results in an average 10% increase in subsidence, especially in shorter piles. Over 60% of total subsidence occurs in the first 200 cycles**,** with more than 20% occurring in just the first 10 cycles**.**

A time-dependent model initially used for scour around piles [15] was applied to subsidence data [14], expressed by:

$$\frac{Y}{Y_e} = a\left\{1 - \exp\left[-C\left(\frac{t}{T_e}\right)^n\right]\right\} \quad (1)$$

Experimental data fit this model well ($R^2 = 0.99$) for both loose and dense sand. Coefficient values closely align with those reported in previous research [14], supporting the model's validity. Minor differences are attributed to soil gradation and compaction.

Since frequency is variable, number of cycles replaces time as the key parameter:

$$\frac{S}{S_e} = a\left\{1 - \exp\left[-C\left(\frac{N}{N_e}\right)^n\right]\right\} \quad (2)$$

Models were developed for both sand types (loose and dense), enabling estimation of subsidence at any cycle count using average values: $N_e \approx 95$ and $S_e \approx 6$–18 mm.

Post-cyclic static lateral loading tests showed that in loose sand**,** subsidence densifies the surrounding soil, increasing the lateral resistance. In dense sand, rearrangement of particles may reduce or restore the pile's initial load-bearing capacity.

4. Conclusion

-Increasing the pile's embedment depth leads to more subsidence, with the subsidence depth averaging about 3.5% of the embedment length. This is due to soil particle redistribution and convective flow.

-Higher loading frequencies cause more subsidence, with a 10% increase in subsidence depth for each frequency doubling (from 0.07 Hz to 0.14 Hz, and 0.14 Hz to 0.28 Hz).

-The radius of subsidence is directly related to its depth, being 1.8 times the depth in loose sand and 2 times in dense sand, due to compaction and particle redistribution around the pile.

-Loading frequency does not significantly affect the static lateral bearing capacity after cyclic loading. Forces at given displacements were almost identical across frequencies.

-In loose soil, bearing capacity increases by 10% to 50% after cyclic loading due to soil compaction, while in dense soil, it decreases by 5% to 20% due to particle redistribution.

5. References

[1] M. Dolores Esteban, J.-S. López-Gutiérrez, V. Negro, C. Matutano, F.M. García-Flores, M.Á. Millán, Offshore wind foundation design: some key issues, Journal of Energy Resources Technology, 137(5) (2015).

[2] W. Liao, J. Zhang, J. Wu, K. Yan, Response of flexible monopile in marine clay under cyclic lateral load, Ocean Engineering, 147 (2018) 89-106.

[3] Z. Liu, Y. Zhang, Effect of drainage conditions on monopile soil-pile interaction in sandy seabed, Ocean Engineering, 315 (2025) 119826.

[4] R. Owji, G. Habibagahi, M. Veiskarami, An experimental study on the lateral behavior of piles in unsaturated sand under monotonic, cyclic and post cyclic loading, Geotechnical and Geological Engineering, 42(5) (2024) 3171-3191.

[5] G. Yin, F. Niu, J. Luo, J. Wang, M. Liu, T. Dong, Y. Cao, A. Li, High potential for pile-bearing capacity loss and ground subsidence over permafrost regions across the Northern Hemisphere, Global and Planetary Change, 226 (2023) 104156.

[6] Y. Wang, M. Zhu, W. Gong, G. Dai, H. Lu, B. Wang, Lateral behavior of monopiles considering the effects of sand subsidence and densification under lateral cyclic loading, Marine Georesources & Geotechnology, (2021) 1-11.

[7] S.-H. Chong, J.C. Santamarina, Sands subjected to repetitive vertical loading under zero lateral strain: accumulation models, terminal densities, and settlement, Canadian Geotechnical Journal, 53(12) (2016) 2039-2046.

[8] P. Cuéllar, Pile Foundations for Offshore Wind Turbines: Numerical and Experimental Investigations on the Behaviour under Short Term and Long-Term Cyclic Loading, Berlin, Berlin, Germany, 2011.

[9] P. Cuéllar, M. Baeßler, W. Rücker, Ratcheting convective cells of sand grains around offshore piles under cyclic lateral loads, Granular Matter, 11(6) (2009) 379-390.

[10] L. Li, H. Liu, W. Wu, M. Wen, M.H. El Naggar, Y. Yang, Investigation on the behavior of hybrid pile foundation and its surrounding soil during cyclic lateral loading, Ocean Engineering, 240 (2021) 110006.

[11] K. Lesny, J. Wiemann, Design aspects of monopiles in German offshore wind farms, in: Proceedings of the International Symposium on Frontiers in Offshore Geotechnics, AA Balkema Publishing, 2005, pp. 383-389.

[12] P. Tasiopoulou, Y. Chaloulos, N. Gerolymos, A. Giannakou, J. Chacko, Cyclic lateral response of OWT bucket foundations in sand: 3D coupled effective stress analysis with Ta-Ger model, Soils and Foundations, 61(2) (2021) 371-385.

[13] D. Kallehave, C.L. Thilsted, M. Liingaard, Modification of the API py formulation of initial stiffness of sand, in: Offshore Site Investigation and Geotechnics: Integrated Technologies-Present and Future, Society of Underwater Technology, 2012.

[14] J. Li, D. Guan, Y.-M. Chiew, J. Zhang, J. Zhao, Temporal evolution of soil deformations around monopile foundations subjected to cyclic lateral loading, Ocean Engineering, 217 (2020) 107893.

[15] M. Wei, Y.-M. Chiew, D. Guan, Temporal development of propeller scour around a sloping bank, Journal of Waterway, Port, Coastal, and Ocean Engineering, 144(5) (2018) 06018005.