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Centrifuge Modeling of Offshore Pile Response under Inclined Monotonic and Cyclic Loading

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ABSTRACT: As offshore wind technology advances into deeper waters, understanding the performance of foundation systems under complex load paths becomes increasingly important. Inclined pullout loading scenarios are highly relevant to floating wind anchor design. This study investigates the pull-out behaviour of offshore piles under inclined monotonic and cyclic loading using centrifuge modelling at 50g. Tests were conducted in dense sand with load inclination angles of 90°, and 75°. The results show that inclined loading leads to a more gradual mobilisation of resistance and, as the load direction becomes more horizontal, to comparable or even higher capacities than those observed under vertical loading. This response is linked to the development of additional lateral soil resistance under inclined loading, which increases the normal stress acting on the pile shaft and enhances the mobilisation of shaft resistance. Under the range of explored loading paths, cyclic responses remain largely bounded by the monotonic envelope, indicating that cyclic loading alters the mobilisation path rather than the failure mechanism. The findings highlight the importance of accounting for load inclination in the design of offshore mooring foundations.

1 INTRODUCTION

Floating offshore infrastructure, including wind turbines and deep-water oil and gas platforms, depends on mooring systems to maintain stability. These mooring lines transfer loads induced by wind, waves, and currents directly to the anchors. In the site-specific preliminary design prepared for floating offshore infrastructure, the loads acting on mooring foundations are rarely purely vertical. Instead, piles are commonly subjected to inclined loads that may act monotonically during extreme events or cyclically under long-term environmental loading (Randolph & Gourvenec, 2011).

A reliable understanding of pile capacity under inclined loading is therefore essential to prevent excessive displacements, loss of stiffness, and progressive degradation. A significant amount of research has been carried out to investigate the pullout capacity of piles and anchor systems. Early laboratory studies by Rao et al. (2006) showed that pile pullout capacity in marine clay is strongly influenced by embedment ratio and the loading inclination. Their results demonstrated that inclined loading mobilizes both skin friction and passive earth pressure, leading to higher resistance compared to vertical pullout. Later centrifuge studies by Wang et al. (2022) confirmed that increasing the loading angle enhances the passive soil resistance and increases the capacity. These studies also showed that when the load is applied at greater depth, pile head displacement decreases, and the failure mechanism changes from shallow, localized soil yielding to a deeper and more distributed response involving a larger volume of soil. The influence of cyclic loading on pile pullout behavior has also received increasing attention. Centrifuge tests by Luo et al. (2025) revealed that cyclic oblique loading causes cumulative soil displacement and a gradual reduction in pile capacity, with the extent of degradation depending on the cyclic load amplitude, load ratio, and number of cycles. Similar trends were observed in laboratory tests by Krishna and Patra (2006), who showed that cyclic loading leads to increased permanent displacements and reduced pullout capacity, although a partial stabilization or "shakedown" effect may occur after repeated cycles. In addition, installation effects have been highlighted in centrifuge studies on dynamically penetrating anchors, where soil type, consolidation time, anchor geometry, and pullout angle were shown to significantly affect pullout resistance and failure mechanisms (O'Loughlin et al., 2004; Richardson et al., 2009).

Huang et al. (2020) investigated the drained response of rigid piles in sand subjected to inclined tensile loading through centrifuge testing of both rough and smooth piles. Their results showed that the monotonic pile capacity decreased with increasing load inclination, reducing from a maximum under horizontal loading to significantly lower values under vertical loading, particularly for smooth piles. Rough piles developed greater shaft resistance than smooth piles, leading to higher pullout capacities. In addition, the study demonstrated that under inclined loading conditions, the vertical and horizontal pile responses were strongly coupled and could not be treated independently, highlighting the importance of considering load inclination in pile design. Their cyclic loading tests also showed that repeated inclined loading caused permanent displacements to build up over time and gradually reduce the pullout capacity. Rough piles performed better under cyclic loading, showing less degradation compared to smooth piles.

Soriano et al. (2026) examined the performance of suction anchors in a soft kaolin layer using a centrifuge model. Vertical pullout tests showed that suction anchors developed high load-bearing capacity at moderate displacement levels, while pore pressure measurements revealed the formation of a reverse end-bearing mechanism that contributed significantly to the pullout resistance. Results from multidirectional loading paths showed that changes in load direction influenced the soil stress response and pore pressure evolution around the anchor, leading to different displacement trends and failure mechanisms compared to unidirectional loading. These findings demonstrate the importance of accounting for multidirectional loading when assessing suction anchor performance in soft clay.

Recent work has also highlighted the need to evaluate anchor systems within a broader sustainability and design framework for floating offshore wind applications. For example, Foglia et al. (2025) proposed a methodology for selecting sustainable-by-design anchors by integrating economic, environmental, and technological performance indicators into the anchor design process. Their study demonstrated that anchor performance and feasibility depend not only on geotechnical capacity but also on installation requirements, environmental impacts, and system-level considerations associated with floating offshore wind farms. Overall, previous studies show that pile and anchor pullout behavior is governed by a complex interaction between geometry, soil conditions, and loading characteristics. Factors such as the load inclination angle θ, loading history, cyclic loading, compressive preloading, and consolidation state play an important role in determining the anchor pullout capacity. However, much of the existing research has focused on either vertical or horizontal loading, or on specific soil types and anchor configurations. As a result, the influence of load inclination angle has often been treated in a limited or isolated manner, especially when both monotonic and cyclic loading are involved. In real offshore applications, piles are subjected to inclined, multidirectional, and time-varying loads caused by combined wind, wave, and current actions. These inclined loads can significantly affect how forces are transferred to the soil, how displacements accumulate, and how capacity is mobilized. Despite this practical relevance, there is still a lack of comprehensive experimental data examining the combined effects of load inclination angle and cyclic loading on offshore pile pullout behavior at realistic stress levels.

To address this gap, this study investigates the response of offshore piles subjected to inclined monotonic and cyclic loading through centrifuge modelling. The central research question is: How does the load inclination angle influence the pullout capacity and displacement response of offshore piles under monotonic and cyclic loading conditions relative to the pullout structural element? In offshore mooring systems, loads can be transferred to the foundation through either rigid or flexible connections, which results in different load paths and deformation behavior. To reflect this, a series of centrifuge tests was performed in which the load inclination angle was systematically varied between 75° and 90°, and both rigid and flexible rope-type loading connections were used to represent typical offshore. The paper is organized as follows. Section 2 describes the centrifuge modelling approach, including soil preparation, model pile configuration, and loading procedures. Section 3 presents experimental results, with particular emphasis on the effect of load inclination angle on pullout capacity and displacement response under monotonic and cyclic loading. Finally, Section 4 summarizes the main conclusions and outlines recommendations for future research.

2 METHODOLOGY

Centrifuge testing was adopted to investigate offshore pile pullout behavior under inclined monotonic and cyclic loading at realistic stress levels. By applying an augmented centrifugal acceleration to scaled models, centrifuge modelling overcomes the limitations of both small-scale and full-scale testing and allows prototype stress conditions to be accurately reproduced. The tests were designed to represent an offshore pile behavior under inclined loading conditions typical of floating offshore systems. A scaling factor of N = 50 was adopted. All tests were conducted at the 2.4 m diameter geotechnical centrifuge at Delft University of Technology (Allersma, 1994). The usable carrier volume measures 560 × 350 × 210 mm (i.e., height × width × depth).

The pullout tests are performed on aluminium, open-ended model piles with a length of 160 mm, a diameter of 40 mm, and a wall thickness of 1 mm. Aluminium was selected for its ease of machining, repeatability in fabrication, and adequate stiffness to weight ratio at model scale, which ensures that the pile response reflects the soil-structure interaction rather than the structural deformation of the model itself. Based on these dimensions and an elastic modulus of approximately 70 GPa for aluminium, the axial stiffness of the model pile, expressed as EA/L, is on the order of 10^8 N/m.

At a centrifuge acceleration level of 50g, the axial stiffness of the prototype pil**e** can be estimated from the elastic stiffness relation $k = EA/L$. Using the prototype dimensions and material properties of the pile, this results in a stiffness on the order of 10^{10} N/m. Two different pullout connections were initially considered for applying the load to the pile. A rigid connection setup was used in which a steel rod was screwed directly into the pile head and connected to a load cell mounted on a 2D actuator (Li et al., 2020). In addition, several tests were performed using a rope connection, where a flexible cable linked the pile head to the load cell and actuator. However, the rope introduced additional compliance into the system, which affected the consistency of the load transfer during testing. Because of these compliance-related issues, the rope connection was not adopted in the final testing program, and the rigid connection was used for the experiments reported in this study. Also, the load inclination is defined by the angle β, measured between the applied load direction and the pile vertical axis, with β = 90° corresponding to vertical pullout and decreasing values of β indicating increasingly inclined loading. The inclined loading angle was achieved by moving the actuator horizontally, which changed the direction of the applied load relative to the horizontal axis of the pile. By adjusting the actuator horizontal position, the load inclination angle β could be controlled while maintaining the applied displacement.

2.1 Soil model

Soil samples were prepared in a cylindrical container with an inner diameter of 290.52 mm and an inner height of 190.1 mm. In this tests, we use medium- to coarse-grained Hokksund sand with properties listed in Table 1. The samples were prepared with the air pluviation method and subsequently compacted using a shaking table, resulting in a final relative density of approximately 80%. All experiments were conducted under dry conditions.

Cone penetration tests were performed at different radial distances from the center of the strong box using a 8 mm diameter mini CPT (Wang et al., 2022) prior to the pile pullout. Profiles of cone tip resistance, q_c, with depth z show consistency in the sample preparation (see Fig. 2).

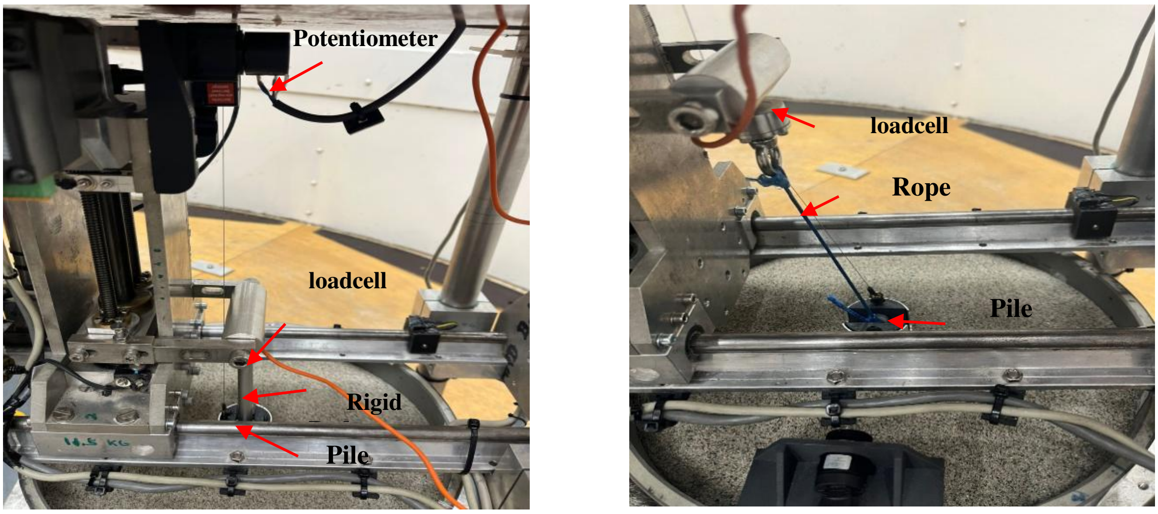
Table 1. hokkSund material properties.

Parameter	Symbol	Value
Median grain size	D_{50}	0.42 mm
Max. void ratio	e_{max}	0.93
Min. void ratio	e_{min}	0.50
Specific gravity	G_s	2.7
Critical state friction angle	φ_c	41°

2.2 Testing plan

The experimental program was designed to study how offshore piles behave when they are pulled out under inclined loading. The tests focus on understanding how the pile response is affected by two main factors: the load inclination angle and the type of loading (i.e., monotonic or cyclic). All other conditions, such as pile geometry, material, and soil properties, were kept the same throughout the tests so that the effect of each variable could be clearly identified. A total of 5centrifuge tests were carried out in this study.

Monotonic tests were performed under displacement control, while cyclic tests were conducted under load control with an amplitude of 40% and a mean load of NNN% the monotonic capacity. The applied load and pile displacement were measured using a load cell together with the actuator encoder and an external potentiometer. For the monotonic tests, a constant displacement rate of 0.1 mm/s was used.



(a) (b)

Figure 1. Pullout loading system with (a) a rigid connection, and (b) a rope.

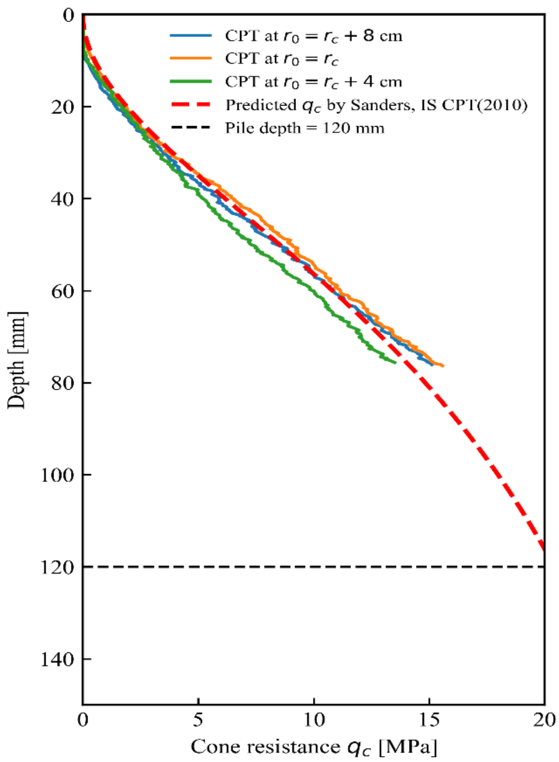
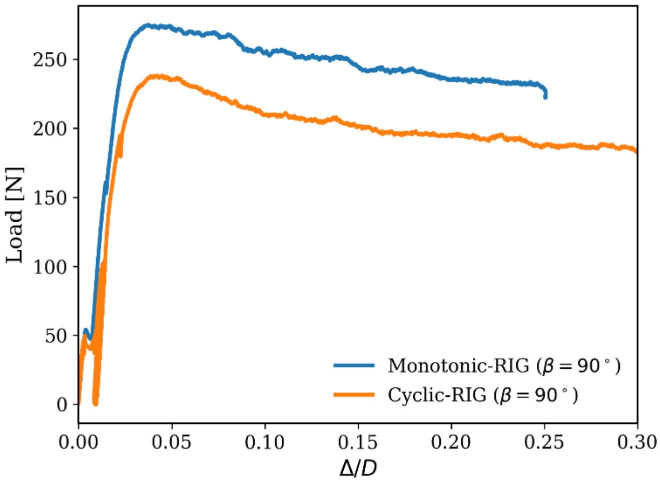


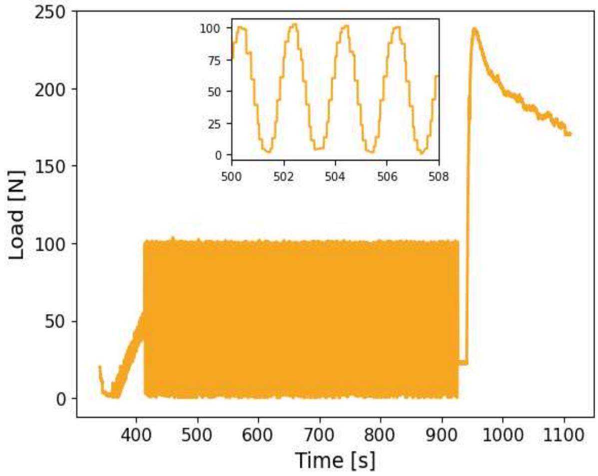
Figure 2. CPT results at different radial distances from the strongbox center.

2.3 Monotonic and cyclic pullout capacity

Typical results from the monotonic tests under vertical (β = 90°) and inclined loading (β = 75°) are provided in Figs. 3 and 4. In all cases, the pullout capacity is reached when the load attains a peak value, after which the resistance decreases with further displacement. When a rigid connection is used, the pile response is generally stiffer, and the peak load is reached at a lower displacement. A rigid connection transfers the applied load directly to the pile head with minimal deformation or rotation, resulting in limited system compliance. Several tests were also performed using a rope connection; however, these tests will be repeated to correct the compliance effects of the rope system. Therefore, the results from the rope connection tests are not presented in this study. Also, after the peak load is reached, the rigid connection shows a gradual post-peak response, with the load decreasing progressively with increasing displacement.

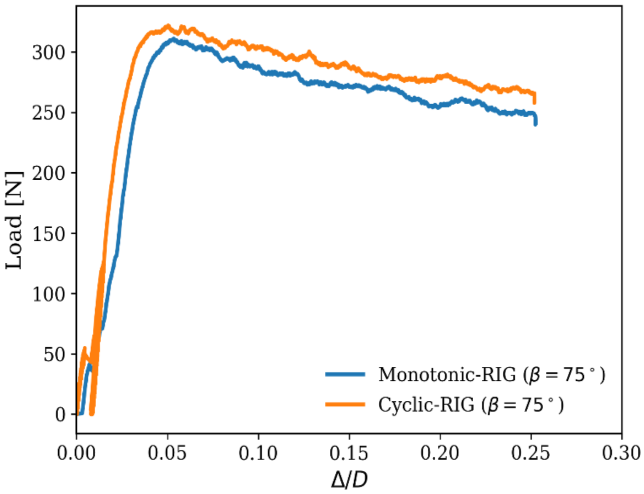
The cyclic load–displacement response generally follows the same trend as the monotonic curve but reaches a slightly lower peak load, with a reduction of about 30 N compared to the monotonic test. This suggests that, for the loading conditions here explored (Figs. 3(b) and 4(b)), cyclic loading affects the mobilisation path of the pile-soil interaction and results in a small reduction in resistance. Here, mobilisation path refers to the way soil resistance develops progressively with increasing displacement, including the effects of unloading and reloading during cyclic loading (e.g., Galvis-Castro et al., 2023). At small displacements, the cyclic response shows a slightly steeper initial slope, indicating a higher apparent stiffness compared to the monotonic

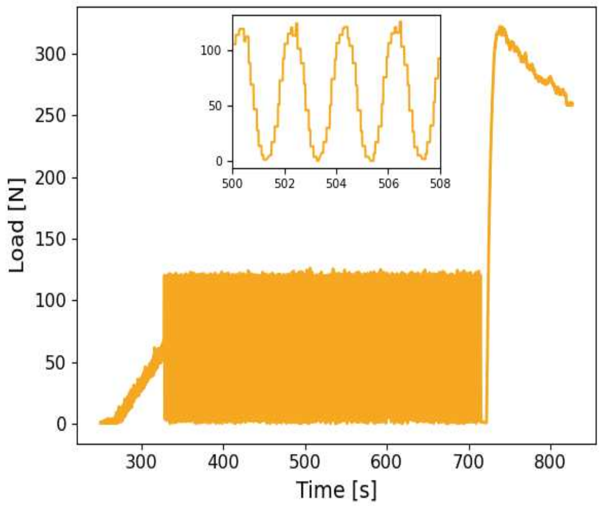




(a) *(b)*

Figure 3. Monotonic and cyclic load vs displacement for a vertical pullout (β=90°) with (a) a rigid connection, and (b) load vs time for cyclic test





(a) *(b)*

Figure 4. Monotonic and cyclic load vs displacement for (a) rigid connection, and (b) load vs time for cyclic test (β=75°)

response. As displacement increases, this difference gradually reduces and the cyclic response approaches the monotonic trend as the pile-soil interface becomes fully mobilised. However, the peak load reached during cyclic loading remains lower, which may indicate some rearrangement or slight degradation of the surrounding soil caused by repeated loading. After the peak load, the rigid connection shows a gradual reduction in load as displacement increases. After the peak load is reached, the rigid connection shows a gradual reduction in load as displacement increases.

The second experimental variable investigated in this study is the load inclination angle, which modifies the relative contribution of axial and lateral components acting on the pile. Introducing load inclination helps to clarify how combined loading influences the mobilisation of shaft resistance compared with pure vertical pull-out. In vertical pull-out, resistance is provided solely by shaft friction acting at the pile–soil interface, as the pile moves without inducing lateral soil resistance. When the load is inclined, however, the pile experiences lateral displacement in addition to upward movement. This leads to the development of passive soil resistance on the loaded side of the pile and active conditions on the opposite side. Although shaft friction remains the main source of pull-out resistance, these additional lateral soil responses change how the resistance is mobilised by increasing the normal stress acting on the pile shaft. Under monotonic loading, inclined pull out leads to a higher and more gradual development of pile capacity. Under cyclic loading, the response is still bounded by the monotonic envelope, Cyclic tests show slightly higher peak capacities than monotonic loading, in contrast to observations from cyclic pull out reported in previous studies, like in Huang et al., 2020. Furthermore, the cyclic load combinations used in this study lie within the stable domain of the cyclic loading stability diagram commonly used for offshore foundations (Cerfontaine.,B et al,.), where cyclic loading is not expected to lead to significant capacity degradation. This explains why the post-cyclic monotonic capacity observed in the tests remains similar to the monotonic capacity. Overall, these results show that vertical tests alone are not sufficient to describe pile behaviour under inclined cyclic loading, and that load angle plays a key role in controlling the soil-structure interaction and cyclic performance.

Under cyclic loading, the load-displacement response remains broadly within the monotonic envelope. Also, the cyclic test reaches slightly higher peak loads than the corresponding monotonic tests for test with β=75. In summary, the results at β = 75° show that load inclination plays a key role in governing pull-out behaviour. Inclined loading affects how shaft resistance is mobilised and increases the sensitivity of the pile response to cyclic loading, while the connection type mainly influences the rate and stability of degradation.

3 CONCLUSIONS

This study was motivated by the need to better understand the pull-out behaviour of piles in sand subjected to cyclic tensile loading, particularly when the load is inclined rather than purely vertical. Such loading conditions are common in offshore and anchored structures, yet they are often simplified in design by assuming vertical loading and rigid connections. The goal of this work was therefore to investigate how load angle influence pile pull-out behaviour under monotonic and cyclic loading. To achieve this, a series of centrifuge tests at 50 g were performed on model piles in drained sand, considering two load angles. The results show that cyclic loading modifies the mobilisation of pull-out resistance compared to monotonic loading, with a higher apparent stiffness at small displacements and a more progressive development of resistance as displacement increases. Load inclination alters the mobilisation process and can lead to comparable or higher pull-out capacities at moderate angles compared to vertical pull-out, while also producing a smoother load–displacement response. Overall, the pile response is shown to be sensitive to loading conditions. Future studies could extend this work by exploring a wider range of loading angles, cyclic loading amplitudes, and numbers of cycles, as well as different sand densities and further improvements in the pile-rope compliance.

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