Engineering Challenges and Lessons Learnt from Centrifuge Modelling of Monopile–Clay Interaction

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ABSTRACT: This contribution reports on the practical challenges and engineered solutions encountered during centrifuge model tests within the MIDASclay project, which investigates monopile clay interaction under cyclic lateral loading. Tests were conducted in the Deltares geotechnical centrifuge employing densely-instrumented large-diameter (10 m at prototype scale) aluminium monopiles. Achieving realistic over-consolidated soil conditions required extensive sample preparation and the development of drainage concepts combining horizontal sand layers with vertical drains to accelerate consolidation under high vertical stresses. Installing wished-in-place monopiles proved demanding due to the high undrained strength of the clay, leading to a bespoke installation approach. Lateral loading at high g-levels required careful engineering to avoid oscillation at the pile-actuator interface and to remain within actuator stroke limits, while additional challenges arose, including larger-than-expected pile settlement during cyclic loading. Instrumentation of monopiles and soil also posed challenges, with lessons shared to guide future experimental practice. These difficulties prompted iterative redesigns in interfaces, sensor mounting, and calibration protocols. Alongside selected first-order results, the paper reflects on both the successes and shortcomings of these strategies, highlighting the intricacies of centrifuge monopile testing and offering guidance for future soil-structure interaction studies.

1 INTRODUCTION

A significant share of the remaining economically feasible offshore wind sites is underlain by cohesive soils, making the understanding of monopile behaviour in clay increasingly critical for the reliable design and long-term performance of fixed-bottom foundations. This is particularly relevant under cyclic lateral loading, where clay stiffness, strength degradation, and accumulated deformations govern serviceability and fatigue performance over the operational lifetime of offshore wind turbines. Within this context, the MIDASclay project (Kementzetzidis et al., 2025) aims to advance the understanding of cyclic monopile–clay interaction through coordinated physical and numerical modelling, with the objective of informing improved engineering models for monopile design in cohesive soils.

Despite the central role of centrifuge testing in advancing the understanding of monopile–soil interaction (Lai et al., 2020; Alsharedah et al., 2023; Wang et al., 2023), the practical challenges associated with modelling large-diameter monopiles in stiff, over-consolidated clays under cyclic loading are rarely documented in the literature. These challenges, which span sample preparation, pile installation, loading control, and instrumentation reliability, can strongly influence data quality and experimental feasibility. Against this background, the present paper reports on important engineering challenges encountered during the MIDASclay centrifuge campaign and the solutions developed in response, with the aim of providing practical guidance for future experimental studies on monopile–clay interaction. Accordingly, the following sections provide a concise description of the centrifuge test setup to contextualise the engineering challenges discussed, rather than a comprehensive account of the experimental programme and the results.

2 DESCRIPTION OF THE TESTS

The centrifuge tests in MIDASclay project were conducted using the geotechnical centrifuge facility at Deltares. The Deltares centrifuge is a beam centrifuge manufactured by Actidyn (Model C72-3), with a radius of 5 m and a maximum payload capacity of 260 g-tonne.

The tests were performed in a circular strongbox with an internal diameter of approximately 0.9 m, allowing the installation and testing of three model monopiles within a single clay specimen. The monopile layout within the strongbox was carefully defined via dedicated numerical sensitivity analysis to minimise boundary effects and pile-pile and pile-rigid-boundary kinematic interactions. Figure 1 illustrates the experimental setup together with the basic details of the instrumentation layout.

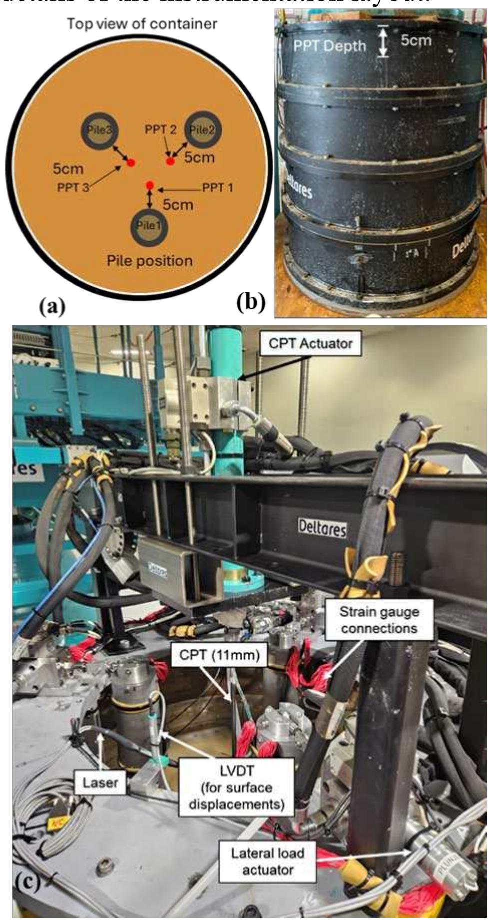


Figure 1. Experimental setup: (a) schematic layout showing monopile positions b) pore pressure transducer (PPT) burial depths; (c) overall view of the test setup..

The clay bed was prepared by making use of commercially available Vingerlink clay bricks which were stacked inside the strongbox and consolidated under 1-g conditions to overburden stresses of 300 and 600 kPa with particular emphasis placed on high consolidation pressures that resulted in stiff clay behaviour at model scale. Vingerlink K147 is a low-to-medium plasticity clay (LL ≈ 36%, PI ≈ 21%) with a saturated unit weight of about 19.6 kN/m³ and a consolidation coefficient in the order of 10^{-8} m²/s, indicative of slow drainage behaviour.

The instrumentation layout and the particulars of the soil model are further illustrated in Figure 2. The aluminium monopiles with a wall thickness of 4.5 mm and a diameter of 100 mm were instrumented with a dense array of strain gauges on opposing sides of the pile.

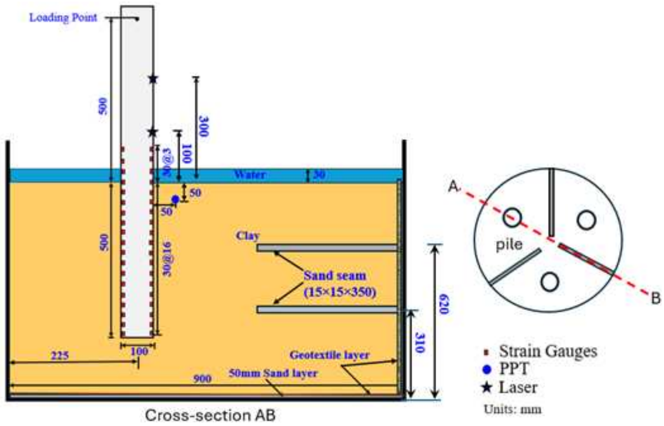


Figure 2. Cross-section of the experimental setup highlighting the instrumentation and sand seams

The following sections describe the principal engineering challenges encountered during consolidation, pile installation, lateral loading, and measurement, together with the solutions developed in response. Where appropriate, selected observations from the tests are referenced to illustrate the implications of these challenges for experimental performance and data reliability.

3 ENGINEERING CHALLENGES AND SOLUTIONS

3.1 Sample Preparation and Consolidation

Achieving a stiff, over-consolidated clay profile representative of offshore sites was a primary experimental challenge. Although commercially available pre-consolidated clay bricks were used, the initial clay bed height of approximately 1 m still resulted in prohibitively long consolidation times due to the low permeability of the material.

To accelerate consolidation without altering the global geometry of the strongbox, a combined horizontal–vertical drainage system was developed. Horizontal sand seams were introduced at predefined elevations within the clay bed to act as preferential drainage paths, thereby reducing the drainage length during consolidation. These sand layers were hydraulically connected to vertical drainage elements constructed from non-woven geotextiles installed along the inner wall of the strongbox. The vertical drains exploited the in-plane transmissivity of the geotextile material, following the concept proposed by Cengiz and Guler (2017).

Given the high confining stresses imposed during consolidation (up to 600 kPa), special care was required to preserve the hydraulic functionality of the drains. To prevent collapse or clogging of the geotextile pore structure, a composite protective sheath was installed, consisting of a rigid screen sandwiched between the geotextile and the strongbox wall. Owing to the impermeable nature of the strongbox boundaries, this integrated drainage network was essential for effective pore-water dissipation.

3.2 Pile Installation and pile-soil contact

Upon consolidation to an overburden pressure of 600 kPa, the clay stiffness increased substantially, rendering wished-in-place monopile installation particularly challenging. Achieving adequate pile–soil contact without excessive disturbance was essential for reproducing a realistic lateral response- which in turn could be numerically verified.

The installation strategy relied on forming a pilot hole in the consolidated clay, followed by pile insertion. Initial pilot centrifuge tests were conducted to assess feasible installation approaches and their influence on pile–soil coupling. These early tests employed a hand auger with a diameter equal to the pile outer diameter (100 mm), fully coring the clay to the target embedment depth. This approach resulted in inadequate pile–soil contact and produced a softer-than-expected initial lateral response.

To improve mechanical coupling between the monopile and the surrounding clay, the drilling diameter was reduced to 95 mm in subsequent tests, creating a slight interference fit upon pile insertion. In parallel, a deliberate clay plug was retained at the pile base by limiting the coring depth to 1–1.5 pile diameters shorter than the target embedment depth. As a result, the soil was not cored along the full pile length, enabling intimate contact between the pile wall and the surrounding clay while ensuring mobilisation of base resistance during lateral loading.

After drilling, the piles were pushed to their target embedment depth using dead weights, allowing the surrounding clay to deform around the pile shaft. The centrifuge container was then spun at the target acceleration for a few days prior to lateral loading, further enhancing pile–soil contact through stress redistribution and creep as seen in Figure 3.

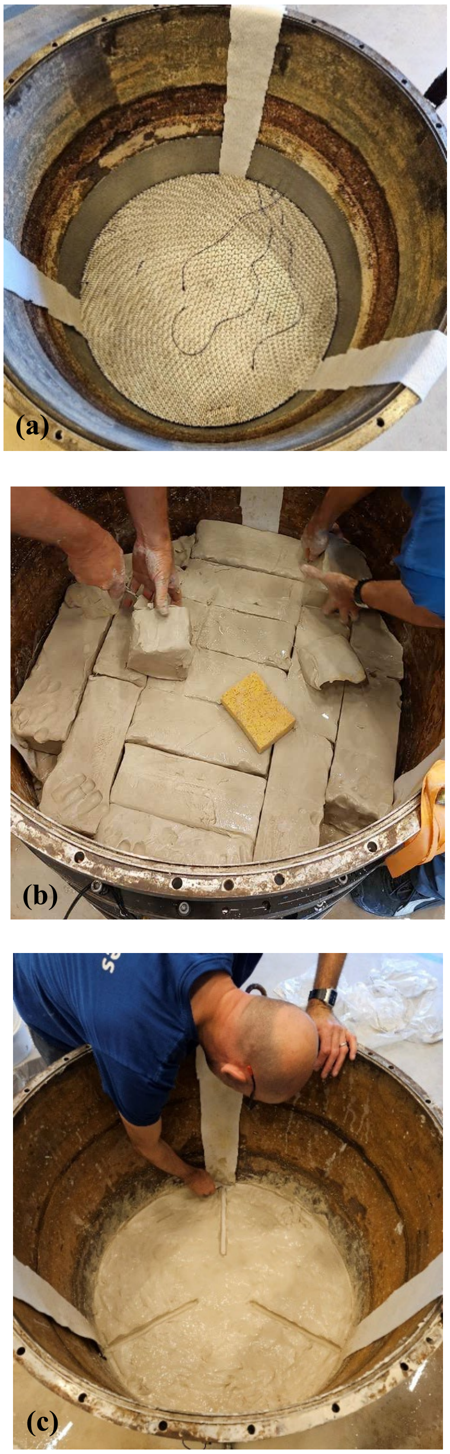


Figure 3. Preparation of the clay bed (each layer is inundated under water after installation of the horizontal sand seams). In (a) empty container with vertical drainage geotextiles; (b) blocks placed; (c) after tamping.

Based on the pilot tests, a plug length of approximately 1–1.5D was adopted for the main test series, providing a practical balance between effective pile–soil coupling and achievable installation in highly consolidated clay. However, under cyclic loading at very large load amplitudes, this plug length proved insufficient to fully restrain vertical pile movement, leading to undesirable pile settlement. To address this limitation, later tests were conducted with an increased plug length of approximately 2D. This modification substantially reduced vertical settlement during cyclic loading and provided a more robust installation configuration under extreme loading conditions. (See Figure 4)

Figure 4. Photo depicting the robust mechanistic connection between the pile and the clay

Finally, accurate pile positioning and verticality were ensured throughout the installation process using a rigid, detachable stencil frame that guided both drilling and pile insertion while protecting the strain-gauge cabling. This measure minimised eccentricity and alignment errors that could otherwise influence the measured lateral response. Figure 5 illustrates the final installation procedure.

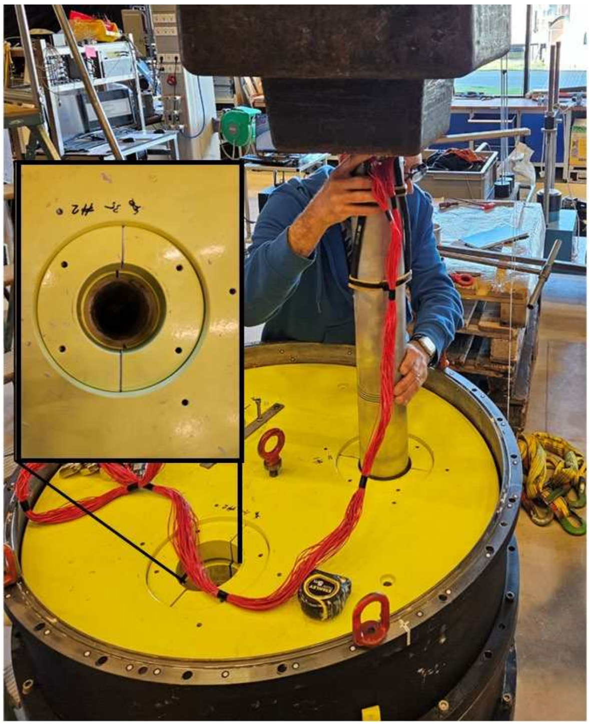


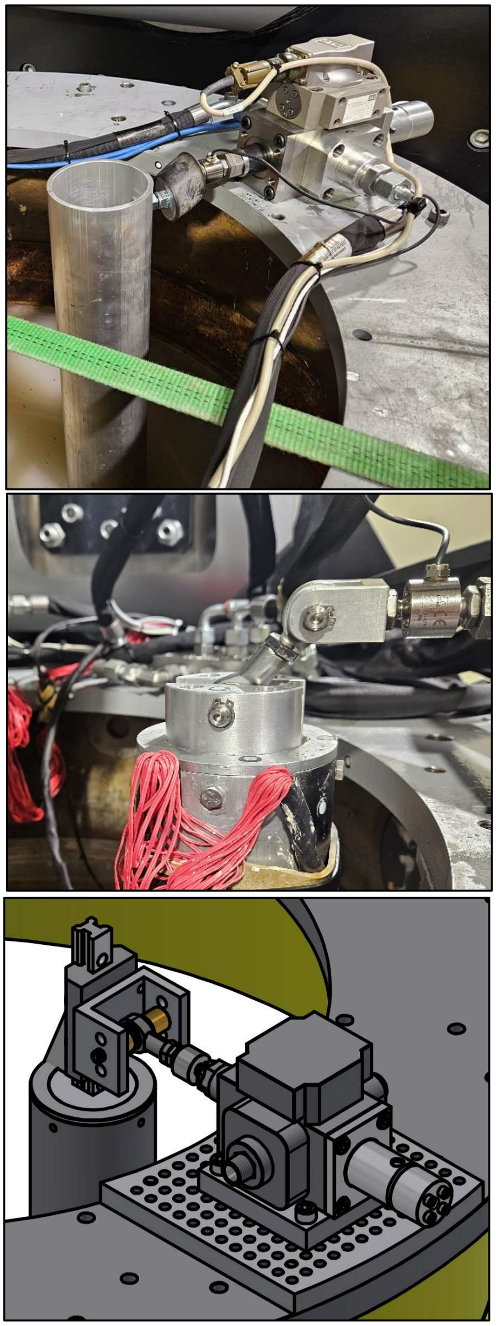
Figure 5. Dead-weight assisted installation of the model monopile. The inset shows the pile guide used for alignment, it is deliberately detachable as it protects the strain-gauge cabling.

3.3 Load Application and Control

Monopiles were subjected to cyclic lateral loading using horizontally mounted hydraulic actuators with a maximum stroke of 50 mm. The actuators operated under closed-loop control with a feedback frequency of 4.8 kHz, enabling precise force and displacement control under high g-levels. Despite this, maintaining stable load application proved challenging due to sensitivity of the control system to changes in stiffness and pile settlement.

Initial loading configurations were vulnerable to loss of actuator set-point, which occasionally triggered non-physical oscillations as the controller attempted to satisfy force and displacement targets simultaneously. To mitigate this behaviour, an elastomer bearing was introduced between the actuator and the pile load point during early tests, providing additional damping during load reversals.

To further enhance control stability, a more robust dynamic controller (MOOG), commonly used in shake-table applications, was implemented in the centrifuge system (Cengiz and Guler, 2017; Fiorentino et al., 2019)., with a feedback frequency of 4.8 kHz, allowing accurate control of force and displacement during cyclic loading. Figure 6 illustrates the loading interface iterations done in the experimental program. Furthermore, Figure 7 illustrates a comparative plot of two identical piles with an embedment depth of 5D. The loading progresses as anticipated in Test 1 but the control system caused oscillations in Test 2, as seen from the force displacement curves.



(a)

(b)

(c)

Figure 6. Load application interfaces used during the test programme: (a) elastomer bearing interface, (b) non-moment-resisting configuration, and (c) updated interface incorporating settlement compensation with a rotating clevis connection.

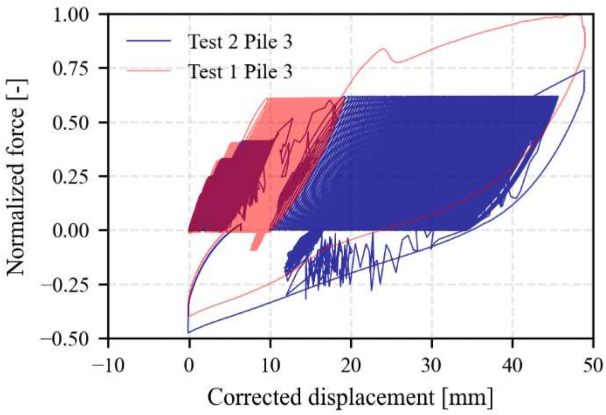


Figure 7. Load-displacement curves pertaining to the equivalent piles with and without actuator oscillations

3.4 Measurements and Reliability

3.4.1 Pore Water Pressure Gauges.

Pore water pressure transducers (PPTs) were used to monitor both consolidation behaviour and cyclic pore pressure response around the monopile. During consolidation, sensors were installed both within the clay and at the strongbox wall, while shallow PPTs were deployed near the pile to capture cyclic pore pressures induced by lateral loading.

Repeated sensor failures were encountered under high confining stresses, particularly at consolidation pressures of 600 kPa. These failures were primarily mechanical, affecting both sensor housings and cabling. Wall-mounted sensors reduced handling damage but raised concerns regarding stress decoupling and boundary effects.

To overcome these limitations, a third measurement strategy was adopted in which PPTs were placed outside the clay specimen and hydraulically connected to the target locations using plastic tubing. To prevent tube collapse under high stress, each tube was reinforced internally with steel wires, preserving a continuous void for pressure transmission.

Typically, six PPTs were employed: three near the strongbox wall at depths of approximately 30, 60, and 75 cm to monitor consolidation, and three closer to the monopile to capture cyclic response. All sensors were HC-25 units rated to 700 kPa. Early tests revealed that sensors placed too close to sand drainage layers produced unrealistically low readings; subsequent tests relocated sensors to elevations unaffected by drainage.

3.4.2 Pile Lateral Displacement

Lateral pile displacement was primarily obtained from actuator feedback signals. However, independent verification was required, particularly at elevations below the load application point. Initial attempts employed laser displacement sensors targeting the pile shaft.

Laser-based measurements proved unreliable due to the curved pile geometry and the reflective metallic surface, which caused unstable signal reflections. Painting the pile surface improved signal quality but did not eliminate geometric sensitivity. Mounting a flat target plate on the pile significantly improved reflection stability, yet operational issues persisted due to power fluctuations and occasional sensor re-initialisation failures in the centrifuge environment. Additionally, reflections from free water near the pile further degraded signal quality.

Given these cumulative issues, a mechanical measurement system was adopted. Spring-loaded pull-wire transducers were installed to maintain continuous physical contact with the pile (the spring force is sufficiently small that it does not influence the test response). These devices performed robustly under high g-levels and were unaffected by the relatively low cyclic loading frequencies applied.

3.4.3 Surface Scanning

Surface scanning was employed before and after testing to document global and local deformation features. Infrared reference markers installed on the monopiles and along the strongbox rim enabled consistent spatial registration of scans across test stages.

The scans allowed reconstruction of surface profiles and identification of deformation patterns associated with loading. In tests involving in-flight overburden plates (which were set to apply 600 kPa of stress), measurable surface inclination of about 2.5° was observed. These data provided a non-contact means of validating qualitative observations and assessing global deformation trends. Figure 8 presents an example of the scanning output.

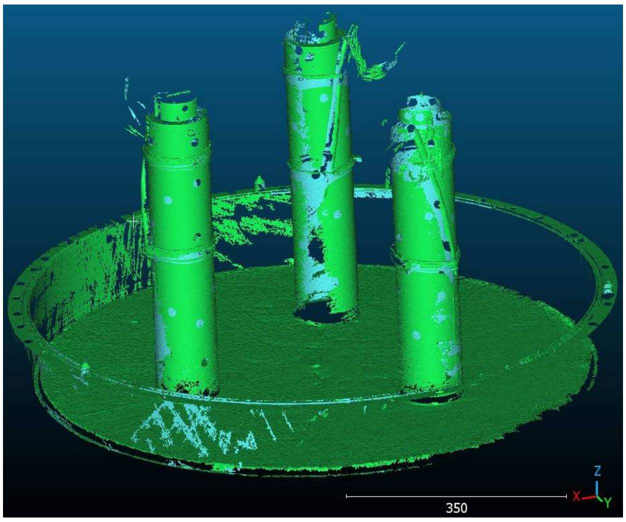


Figure 8. A snapshot of the surface scan data

3.5 Removal of Clay: Electro-osmosis

Following completion of the tests, electro-osmosis was employed to facilitate removal of the highly consolidated clay specimen. A direct current was applied between electrodes placed near the centre of the clay bed and at the strongbox wall, inducing pore-water migration toward the periphery. This process lubricated the clay–wall interface and significantly eased extraction of the specimen without mechanical damage.

4 CONCLUSIONS

This paper has documented key engineering challenges encountered during centrifuge modelling of large-diameter monopiles in stiff, over-consolidated clay, together with solutions that proved effective through iterative testing. Accelerated consolidation was achieved successfully using combined horizontal sand seams and vertical geotextile drains, which reduced consolidation time by approximately an order of magnitude and should be adopted when modelling low-permeability clays at high stress levels. Wished-in-place installation was only reliable when drilling diameters were slightly smaller than the pile diameter and when a soil plug of at least 1.5–2D was retained; full-diameter coring and short plugs led to poor pile–soil contact and excessive settlement and should be avoided. Stable cyclic loading required settlement-tolerant load interfaces and robust dynamic control; rigid load connections and short plugs resulted in loss of control and non-physical oscillations.

Instrumentation was most reliable when pore-pressure sensors were externalised and hydraulically connected, and when mechanical pull-wire transducers were used for displacement measurement; embedded sensors and optical systems showed high failure rates under high stress and high-g conditions. Overall, centrifuge modelling of monopiles in stiff clay demands deliberate engineering beyond standard practice, and future studies should adopt these proven strategies while avoiding installation and measurement approaches that were shown to compromise data quality.

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