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Centrifuge testing and numerical modelling of cyclically loaded monopiles in clay: Setup and early findings of the MIDASclay project

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ABSTRACT: The MIDASclay project (Monopile Improved Design via Advanced Cyclic Soil Modelling in Clay) aims to evaluate the cyclic lateral behaviour of monopiles in clays and clay-sand mixtures, focusing on developing a cyclic soil reaction model that captures cyclic ratcheting and operational stiffness in cohesive soils. Together with the MIDAS project – aimed at cyclic behaviour of monopiles in sand, it seeks to establish a comprehensive framework for modelling the cyclic lateral response of monopiles across diverse soil conditions. To address knowledge gaps, the project employs centrifuge testing of monopiles under cyclic lateral loads, aiming to produce a soil reaction model tailored to cohesive soils. This paper outlines the project setup, research plan, and initial findings. Early results from an auxiliary centrifuge test highlight the preparation of highly over-consolidated samples and provide insights into the influence of clay properties on monopile behaviour. MIDASclay is expected to support and advance design methodologies for monopiles in cohesive soils.

Keywords: monopiles; clay; cyclic lateral loading; centrifuge testing; numerical modelling

1 INTRODUCTION

In recent decades, the pursuit of renewable energy has become a cornerstone in global efforts to combat climate change and achieve energy independence. Among the various renewable sources, offshore wind energy has emerged as a key and scalable solution, particularly as technological advancements continue to drive down costs and improve efficiency. Projections indicate that the global offshore wind capacity could reach an impressive 2000 GW by 2050 (Williams, & Zhao, 2023).

The majority of offshore wind installations are currently located in the North Sea, where favourable seabed conditions and relatively shallow waters have enabled the widespread adoption of monopile foundations. To date, most offshore wind farms along the European shorelines have been developed in sandy environments, leading to research and engineering advancements in cyclic lateral monopile behaviour being predominantly focused on these soil types. However, several areas within the North Sea feature clay soils at depths critical to foundation design, where understanding of monopile performance under cyclic loading remains limited. Furthermore, as offshore wind expands to regions such as the Baltic Sea, the Atlantic Ocean, and increasingly to Asia, Australia, and Africa (Williams, & Zhao, 2023) diverse geotechnical conditions are anticipated, with a growing prevalence of cohesive soils. Notably, in the Baltic Sea, overconsolidated clays have been identified at depths relevant for monopile foundation design (Jensen et al., 2023; Solhjell et al., 2024). This progression underscores the urgent need for enhanced understanding and bespoke design methodologies for monopiles in cohesive soils.

1.1 MIDASclay

The MIDASclay project, led by TU Delft with support from the Dutch consortium GROW, builds on the

MIDAS project (Pisanò et al., 2022; Kementzetzidis et al., 2023b; Pisanò et al., 2025), which focused on the cyclic lateral behaviour of large-diameter monopiles in sands. MIDASclay aims to extend this framework to overconsolidated cohesive (clay) soils, clay-sand mixtures, and layered clay-sand profiles, officially launching in March 2024.

The research programme is conducted in collaboration with partners bringing together expertise across the offshore wind supply chain, involving wind farm developers, turbine manufacturers, marine contractors, and research institutes. To achieve its research goals, MIDASclay will build on a comprehensive testing programme, including laboratory material testing, centrifuge testing of laterally loaded monopiles, and numerical modelling. The combined outcome of the MIDAS and MIDASclay projects is expected to be a framework for simulating cyclic soil-monopile interactions in diverse soil conditions.

2 RESEARCH BACKGROUND

The topic of cyclic monopile behaviour under environmental loading conditions in sandy soils has been a subject of considerable academic and industry interest in the past decade. Overall, it is clear that the challenging features of monopile response to cyclic loading emerge from the complex cyclic behaviour of the geomaterial. To date, there is sufficient evidence to support that under drained conditions monopiles in sandy soils will accumulate deformations (ratchet) in a decreasing rate while simultaneously increase in stiffness. Limited studies have been conducted in sandy soils under realistic hydraulic drainage conditions with evidence suggesting that under low loading amplitudes, hydromechanical coupling will result in a stiffer foundation response compared to drained conditions (Kementzetzidis et al., 2021; Li et al., 2019), but with increasing monopile motion pore water pressure development may lead to undesirable outcomes (Kementzetzidis et al., 2019; Liu & Kaynia, 2023). Opposite to sand, little research has been conducted on the cyclic behaviour of offshore monopiles in cohesive soils. It is anticipated that features of the (cyclic) material behaviour will impact the global monopile response, some of which are (i) cohesion, (ii) remoulding/sensitivity and cyclic degradation, (iii) strain-rate dependence, (iv) ratcheting and (v) post-cyclic reconsolidation effects. Some of these effects are not exclusive to clay soils and may also occur in coarse-grained materials. Notably, load rate effects can be significant in water-saturated sands (Li et al., 2019), while pile–soil gapping has been observed in piles in contact with unsaturated sand topsoil (Kementzetzidis et al., 2023a).

Numerical and experimental studies have explored several traits of cohesive soil behaviour relevant to monopile foundations. Pile–soil gapping has been observed in small-scale (1g and centrifuge) tests and field investigations in both soft clays and unsaturated sands (Hong et al., 2017; Kementzetzidis, et al., 2023a; Kou et al., 2022)– see Figure 1. Ratcheting behaviour has been investigated both experimentally and numerically (Martin et al., 2023; Staubach et al., 2023); (Wu et al., 2022; Wu, 2022) conducted small-scale tests in saturated stiff clay and reported significant load rate effects on monopile rotation accumulation (ratcheting rate) -see Figure 1, while such effects were reported negligible in dry sands. Lai et al., (2020), conducting centrifuge tests in normally consolidated clay, examined the impact of post-cyclic

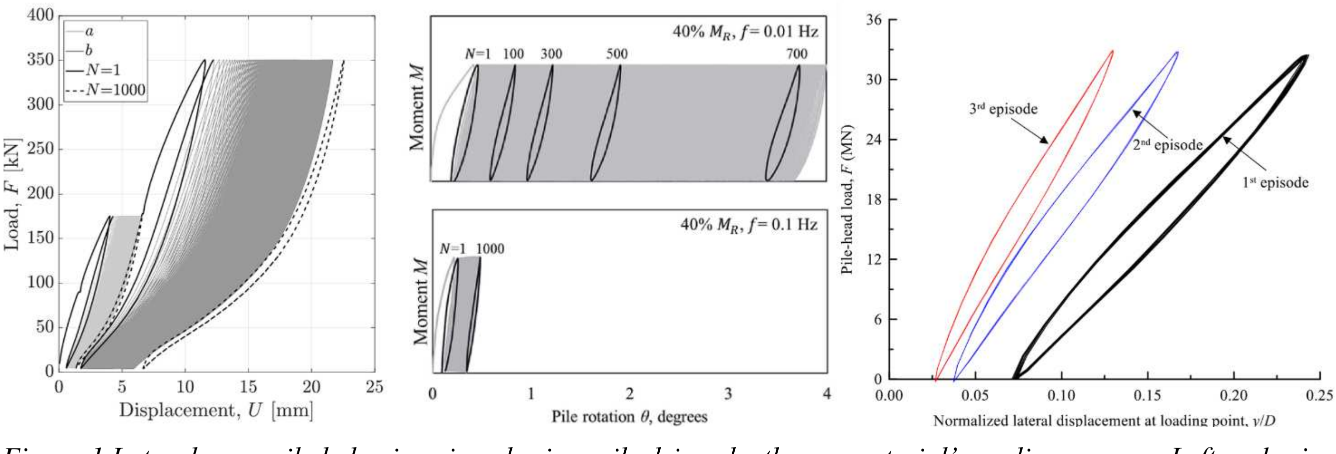

Figure 1 Lateral monopile behaviour in cohesive soils driven by the geomaterial's cyclic response. Left: cohesion in unsaturated sand enabling pile-soil gapping. Force-displacement response showing distinct locking behaviour. Middle: load-rate effects on pile rotation accumulation. Right: impact of post-cyclic loading reconsolidation on lateral stiffness. Figures reproduced with permission from Kementzetzidis et al. (2023a), Wu et al. (2022) and Lai et al. (2020).

reconsolidation and found a notable increase in monopile stiffness and capacity. While these individual features of monopile behaviour have been observed and documented, they have not yet been examined comprehensively in the context of offshore monopile design—an effort this study aims to address.

3 PHYSICAL TESTING OF MONOPILES IN OC CLAYS

Laboratory clay element testing and lateral load centrifuge tests on scaled monopiles will be conducted at the Deltares physical modelling laboratory in Delft. Designing this experimental programme involves various considerations, from material selection and soil preparation to test planning, which are outlined in the upcoming section. To address major uncertainties, particularly in sample preparation, the research team conducted an auxiliary (pilot) centrifuge test. Selected results from this test are presented in Section 4.

3.1 Clay: Vingerlink K147

The clay material selected for this study was Vingerlink K147, offered by Sibelco GmbH – index properties are presented in Table 1 and particle size distribution curve in Figure 2. The material is delivered in prepacked consolidated blocks of 120 mm x 120 mm x 250 mm.

An extensive laboratory testing programme is planned, encompassing monotonic, cyclic, and dynamic tests to achieve the following objectives: (i) material characterisation, (ii) assessment of small-strain stiffness, (iii) evaluation of Su-OCR- $\sigma'_{v,0}$ dependence, and (iv) construction of cyclic contour diagrams (Andersen, 2015).

Table 1. Index properties of Vingerlink K147 clay

Property, unit	Value
Saturated unit weight, γ_{sat} [kN/m^3]	19.6
Liquid Limit, LL [%]	36.2
Plastic Limit, PL [%]	15.1
Plasticity Index, PI [%]	21.1
Consolidation coef., c_v [m^2/s]	~$2\cdot10^{-8}$

3.2 Monopile dimensions and instrumentation

The centrifuge testing programme will investigate two large-diameter monopiles, with prototype-scale dimensions (scaled at 100g) of D = 10 m and embedment depths of L_{emb} = 30 m and 50 m, respectively. The monopiles will be instrumented to measure lateral deflection and rotation at the mudline, while the response below the mudline will be inferred using closely spaced axial strain gauge sensors.

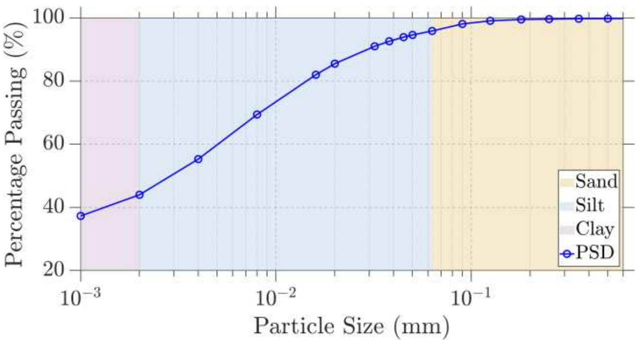

Figure 2 Particle size distribution curve for Vingerlink K147 clay.

3.3 Soil preparation and measurements

The strongbox used in the experimental testing programme has a diameter of 900 mm and a depth of 960 mm. Numerical sensitivity studies confirmed that it can accommodate three monopiles during flight with minimal interference. Boundary effects—specifically the distances between the monopiles and the side and bottom boundaries—were also examined and found to be negligible, provided that monopile positioning was carefully selected. Preparing overconsolidated soil samples is a time-intensive process, particularly given the centrifuge box size. High OCR samples are targeted because soft soils are generally less suitable for monopile foundations. To accelerate consolidation, drainage layers will be introduced at selected locations, with dimensions and positioning verified numerically to minimise their impact on monopile lateral performance.

A range of sample preparation strategies is envisaged, including 1-g and in-flight pre-consolidation, each expected to yield different OCR and Su profiles. Figure 3 shows OCR-depth profiles expected with three preparation methods for Vingerlink clay:

- **Option I**: Pre-consolidation at 1g up to 600 kPa vertical stress.
- **Option II**: Pre-consolidation at 100g with a 600 kPa vertical stress plus soil self-weight.
- **Option III**: Pre-consolidation at 100g with 600 kPa vertical stress, followed by testing at 50g (equivalent monopile embedment depths: 15 m and 25 m).

Pore water pressure will be measured at key locations to ensure consolidation to target stresses and monitor their evolution during the loading programme.

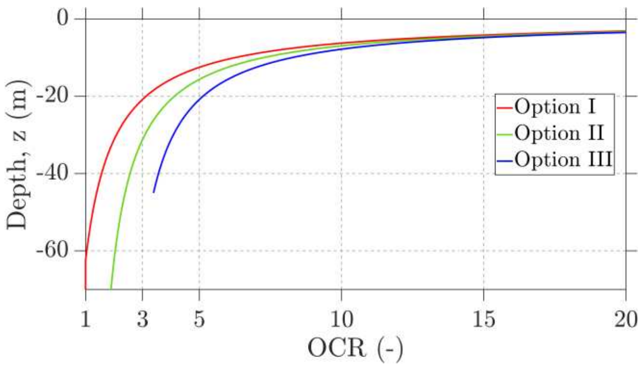

Figure 3. Depth-OCR profiles derived from different sample preparation procedures. Depths reported at prototype scale.

3.4 Lateral loading

The loading programme aims to close knowledge gaps on monopile behaviour in cohesive soils and to develop a reliable model for simulation. Monopiles will be loaded at an elevation of 5D above the mudline, representing the loading eccentricity (horizontal forces and bending moments at the mudline) during ultimate limit state (ULS) storm conditions.

The loading rate will be selected based on the following considerations:

- Ensuring undrained soil behaviour, with consolidation duration accelerated by N^2.
- Accurate monopile-soil dynamics, achieved by scaling frequencies by N.
- Preserving soil strain-rate by maintaining the prototype loading rate,

where Ng is the centrifuge acceleration. For the first point, maintaining undrained behaviour is essential to replicate storm event conditions at prototype scale, imposing a constraint on the minimum loading rate. To evaluate undrained conditions, the normalised velocity $V = vD/c_v$ (where v is velocity, D is diameter, and c_v is the coefficient of consolidation) is commonly used, with $V > 100$ indicating undrained conditions (Randolph et al., 2005). While this criterion has proven effective for CPT, T-bar testing and other geotechnical applications, its direct applicability to laterally loaded monopiles may require further exploration. Studies such as Li et al. (2019) can provide additional insights into this area. Using the method for an infinite monopile under plane strain conditions as discussed by Li et al. (2019), it was estimated that a loading duration of a few hours (conservative estimate) is sufficient to maintain undrained conditions (dimensionless time coefficient $T_p = 0.5$ was selected).

For the second point, accurate representation of the monopile-soil system's dynamic response is essential. Offshore wind turbines (OWTs) predominately oscillate near their first natural frequency. Full-scale tests on a 5 m diameter, 24.05 m embedded monopile — conducted prior to installation of the full wind turbine superstructure — have shown frequency-dependence at frequencies above 4 Hz (Kementzetzidis et al., 2021), or 400 Hz at model scale, well above the frequencies considered in this study. To preserve system dynamics, a maximum loading rate constraint is imposed, and it is assumed that loading frequencies below 10 Hz at model scale will not result in substantial inertial effects.

Finally, since cohesive soils exhibit strain-rate dependency, so testing strain rates should align with field conditions (d'Onofrio et al., 1999; Wu, 2022). Assuming equivalent soil stress and stiffness in centrifuge and prototype scales, a field-consistent loading rate should produce comparable soil strain rates in the centrifuge, suggesting cyclic testing at 0.2–0.3 Hz. Given the above considerations, for parcels of 1000 load cycles, a loading rate in the range of 0.1 to 1 Hz satisfies all the above requirements.

Figure 4. Top left – geotextiles used for vertical drainage, top right – assembly of clay blocks prior to hand tamping (bottom left), bottom right- introduction of sand seams for accelerated drainage.

4 EARLY TESTING RESULTS

To address selected questions raised in the previous section, MIDASclay researchers conducted a pilot centrifuge test including sample preparation with Option I and cyclic monopile testing on a monopile with D = 10 m and L_{emb} /D = 5 at prototype scale (100g acceleration).

Sample preparation involved assembling Vingelink clay blocks in a preconsolidation container (1g consolidation) up to a height of 90 cm, with sand seams added to accelerate consolidation (see Figure 4). During sample construction, pore pressure transducers (PPTs) were installed at three elevations to monitor the consolidation process. The consolidation process was applied in 14 steps to ensure uniform consolidation, resulting in a post-consolidation settlement of 166 mm. The PPTs were installed at different positions as reported in Figure 5. **Erreur ! Source du renvoi introuvable.** 6 illustrates the pore pressure readings from the final consolidation step.

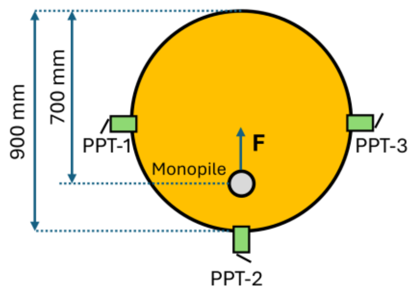

Figure 5. Top view of PPT placement. Sensors were installed at different depths: PPT-1 at z=735 mm, PPT-2 at z=500 mm, and PPT-3 at z=265 mm, measured from the mudline during the soil sample assembly, prior to consolidation. Arrow indicates loading direction.

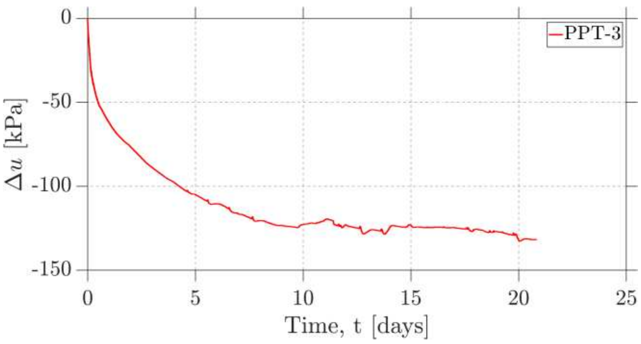

Figure 6. Excess pore water pressure dissipation versus time in model scale (days) during the final consolidation step, as measured by PPT-3 (refer to Figure 5 for sensor positions).

Following consolidation, the monopile was installed by augering a hole of D = 10 cm and L_{emb} = 50 cm, then pushing the pile into place—closely replicating wished-in-place conditions with minimal soil disturbance. In future tests, slightly undersized holes (approximately 0.95 × D in diameter and 1 to 1.5 D shorter than the monopile) will be used to promote tighter shaft–soil contact and ensure full mobilisation of base resistance. After placing the pile at 1g, the sample was spun at 100g in the centrifuge. During flight, the displacement-controlled loading programme shown in Figure 7 was applied at an elevation of 5D; mudline displacement is estimated to be approximately half of the reported displacement. The loading programme included two monotonic loading parcels at various displacement rates, and cyclic loading applied at 0.5 Hz. The monopile's force-displacement response is displayed in Figure 8, showing evidence of:

- Cyclic softening: Force relaxation during fixed displacement amplitude loading cycles
- Monopile-soil gapping: Distinct locking behaviour in the final cycles of the second load parcel – marked as red in Figure 8.
- Rate effects: Significant increase in lateral monopile stiffness (7.5x) with a fortyfold (40x) increase of displacement rate at the onset of the final cyclic load parcel– as indicated by the red arrow in Figure 8.

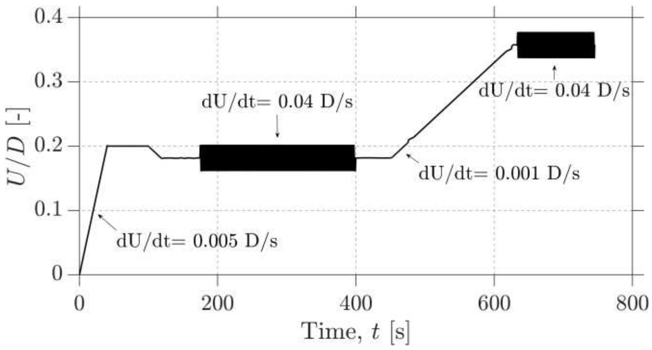

Figure 7. Displacement-controlled loading programme applied and measured at a 5D, with U/D and loading rate inferred at the same elevation. Loading rates are expressed in monopile diameters per second.

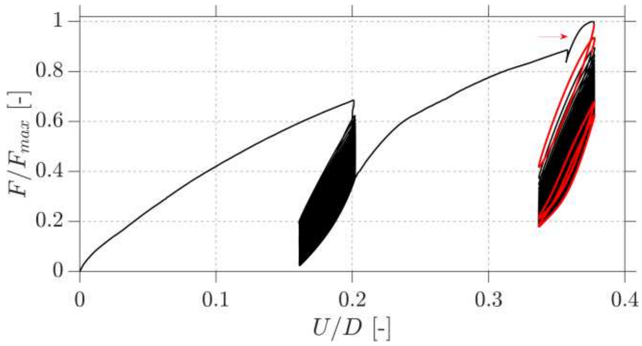

Figure 8. Force-displacement behaviour of the monopile during the loading programme shown in Figure 7. The red loops represent first and last load cycles of the second parcel, while the red arrow indicates the stiffness increase observed during the load-rate increase.

5 CONCLUSIONS

This paper presents the setup and initial findings of the MIDASclay project, which focuses on the cyclic lateral behaviour of monopiles in clays and clay-sand mixtures. It addresses key challenges and engineering solutions related to clay sample preparation, testing setups, and monopile installation. The preparation of soil samples for a pilot centrifuge test is described, along with preliminary testing results. Lateral loading tests reveal geotechnical effects on monopile behaviour influenced by clay cohesion (gapping), cyclic softening, and rate effects (stiffening with increased loading rate). Future tests from the MIDASclay project are expected to provide deeper insights into the complexities of cyclic monopile behaviour in cohesive soils, laying the groundwork for the development of an accurate cyclic soil reaction model for monopiles in clays.

AUTHOR CONTRIBUTION STATEMENT

E. Kementzetzidis: Research conceptualization, Technical leadership, Funding acquisition, Project management, Writing - Original draft. **M. Konstantinou**: Conceptualization, Data collection and curation, Project management, Writing - Reviewing and Editing. **C. Cengiz & R. Zwaan**: Conceptualization, Data collection and curation, Writing - Reviewing and Editing. **A. S. Elkadi**: Funding acquisition, project management, Writing - Reviewing and Editing. **F. Pisanò**, **H. Wang & H.P. Jostad:** Conceptualization, Expert technical advising, Writing - Reviewing and Editing. **G. Christopoulos & D. Mohapatra**: Formal analysis, Writing - Reviewing and Editing.

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