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Centrifuge modelling of an OWT monopile foundation in saturated sand subjected to cyclic dynamic storm loading

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ABSTRACT: Novel centrifuge tests of an Offshore Wind Turbine (OWT) monopile foundation were recently conducted using the 500gton capacity beam centrifuge at the ETH Zurich (ETHZ) Geotechnical Centrifuge Center (GCC). The goal of these tests is twofold: (i) to investigate soil drainage conditions under cyclic storm loading, which are critical in the design and performance of OWT monopile foundations; and (ii) to produce a first-of-its-kind set of high quality, well documented experiments that can be used for validation of advanced numerical models and design optimization. The model was built in a rigid cylindrical box, containing saturated Ottawa sand with Dr ≈ 75% and a steel monopile with an embedded length over diameter (*L/D*) ratio of 3.75. Tested at a centrifugal acceleration of 60g, the monopile was subjected to load-controlled lateral cyclic dynamic loading, applied to the top of the monopile using a custom-designed hydraulic actuator. The paper discusses the design of the centrifuge experiments and the preparation of the model, along with some preliminary results of the lateral cyclic dynamic tests. Selected results are compared to blind predictions made by GR8 GEO prior to testing.

Keywords: OWT monopile, centrifuge test, saturated sand, cyclic dynamic loading, load-control, partial drainage

1 EXPERIMENTAL PROGRAM OBJECTIVE

Europe is the leader in offshore wind, while the European Commission expects the EU to produce at least 240 GW of global offshore wind power by 2050, and wind energy is already critical to several nations' energy infrastructure. Offshore windfarms are also being developed in Asia and the USA, including regions subjected to earthquake and cyclone loads. Currently, most European Offshore Wind farms are founded in dense North Sea sands, and monopiles represent about 80% of installed OWT foundations. The length of these monopiles is usually controlled by either Serviceability Limit State (SLS) or Ultimate Limit State (ULS) cyclic loading; thus, accurate prediction of both the system capacity at failure, as well as the deformation (tilt) at specific load levels before failure are crucial to the economic feasibility of offshore wind farms.

Truly optimizing the performance of OWTs in saturated sand, requires a deep understanding of the complex mechanics of soil–structure–foundation interaction (SFSI) that govern their response under different load combinations and drainage conditions. Key characteristics of soil–foundation system response under cyclic loading, as a function of drainage conditions, are identified below (Tasiopoulou et al., 2020; 2021; Chaloulos et al., 2024):

- In undrained loading, e.g., in low permeability silty sands and/or with larger diameter foundations or high load-levels, foundation stiffness decreases if pore water pressures develop. Indeed, local liquefaction of the soil adjacent to the monopile can occur after many cycles of loading. Due to the high rate of loading, undrained conditions also generally prevail during seismic or ice-loading.
- In fully drained conditions (e.g., clean sands/low load levels), stiffening accompanied by densification is the dominant mechanism.
- In partially drained conditions, dissipation may or may not compensate for the tendency for pore water pressure generation.

Today's design practice for storm loading cases uses simplified methodologies, such as multi-step methods combining monotonic analyses with degraded strength, assuming fully drained or undrained conditions with "rain flow" counting algorithms and empirical charts based on laboratory test data (e.g., Andersen, 2015; Peralta et al., 2017). Assessing the reliability of the design processes has been hampered by:

- Lack of (case studies and/or experimental) data for OWT–foundation systems loaded cyclically to failure/significant deformation levels under partially drained conditions, and
- Limitations in the capability of numerical tools/constitutive models, or availability of computing power to capture the key mechanisms of the complex partially-drained soil-structure interaction process.

Despite the relative youth of the Offshore Wind industry, the lack of failure case-histories are indicative of the "safety" of existing design methods. However, future design optimization will require better understanding of how far the design is from "failure". Thus, there is a strong scientific motivation to conduct experiments that realistically capture the dimensions of OWT foundations, and the soil stress field, as well as loading and drainage conditions. To date several cyclic load-controlled experiments have been conducted on monopiles in sand. These include: i) field tests such as the PISA project (Mc Adam et al., 2020) and ii) centrifuge or model scale tests (summarized in Klinkvort et al., 2012). These tests, however, were all conducted under dry or drained conditions. Takahashi et al. (2022) performed centrifuge tests on monopiles in saturated sand where partially drained conditions were developed; however, the cyclic loads were applied displacement-controlled deviating from the real nature of OWT cyclic loading.

To this end, a novel centrifuge testing campaign is presented in this paper, designed to represent a large-diameter OWT monopile in saturated sand (allowing for partial drainage), subjected to a range of sinusoidal and irregular cyclic loads in a manner that represents the nature of the environmental (storm, typhoon, ice) loads affecting OWT foundations. The objective of this centrifuge campaign is to clarify the complex deformation mechanisms of OWT monopile foundations and provide a well-documented database for validation of state-of-the-art numerical tools. The availability and robustness of such validated tools is a key step towards ULS and SLS design optimization.

2 EXPERIMENTAL SETUP

2.1 Host facility and test equipment

The test campaign was conducted using the Beam Centrifuge at the ETHZ Geotechnical Centrifuge Center (GCC, Figure 1). The 8.25m diameter beam centrifuge can carry a payload of up to 5tons at a centrifugal acceleration of 100g (or equivalently 2tons at 250g). Thanks to its 500gton capacity (currently the largest in Europe), physical models of large dimensions can be tested, allowing for reduction of scale effects and facilitating the use of denser instrumentation. The steel strong boxes used in this test campaign are cylindrical, having a total height h=0.75m, and diameter d=0.75m, allowing for relatively big physical models (in this case an 80 mm diameter monopile) with minimal boundary effects.

An automated custom-built, curtain-type sand raining system was employed for model preparation, allowing for controllable and repeatable model properties. The target relative density is achieved by adjusting the aperture of the hopper, the drop height, and the lateral movement velocity.

Another key aspect of model preparation is related to the saturation process. Given the importance of modelling partially drained conditions, a viscous fluid (Hydroxypropyl methylcellulose powder F50) was used to satisfy centrifuge scaling laws. The 1:60 model scale was selected to optimize prototype model size (4.8m diameter, 18 m embedded length), while still being able to reliably saturate the soil. The facility included an assembly for deaired water, a heating apparatus, thermal cameras and thermometers to monitor temperature, as well as viscometers to evaluate the achieved viscosity. After the preparation of the viscous fluid, the saturation process used the Center's custom-built saturation system, which incorporates $C0_2$ flushing of the model and saturation with controlled flow rates under constant vacuum monitored via manometers.

A key requirement and a novel aspect of this campaign was monopile testing under load-controlled conditions. This was achieved using a custom-built hydraulic actuator, constructed in collaboration with Hagenbuch Hydraulic Systems AG. The dynamic actuator can apply thousands of cycles of loading, used to model long-term wave and storm loading with frequencies of up to 150Hz and loads up to 10kN.

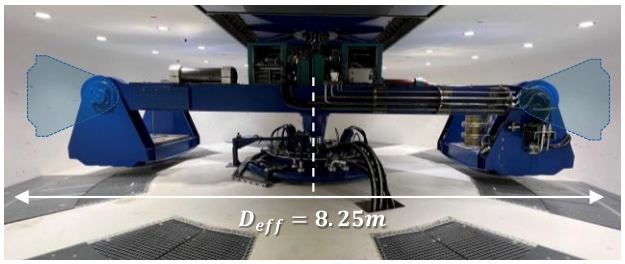

Figure 1. The 500gton capacity ETHZ beam centrifuge.

The newly installed Data Acquisition System of the ETHZ beam centrifuge provides 124 channels, allowing for extensive instrumentation. A wide range of newly acquired sensors, including Lasers, Pore

Pressure Transducers (PPTs), and Load Cells was utilized in the tests. The Center's workshop provided several customized parts, including support frames for the loading and the monitoring devices, as well as the model pile, and the specially designed sliding-hinge connection between the model structure and the actuator. The workshop also installed pairs of strain gauges along the interior of the model pile to measure bending moments. For each sensor, a calibration apparatus was used before each test, to ensure data quality.

2.2 Centrifuge Model Design

The experimental series tested a steel monopile founded in dense (Dr=75-85%), saturated, Ottawa F-65 Sand, under monotonic and cyclic loading (Table 1) at 60g centrifugal acceleration. The loading comprised: (a) slow monotonic lateral pushover; (b) 1-way sinusoidal load-controlled packages of increasing amplitude at different target frequencies; and (c) packages of irregular storm load time-histories of increasing intensity. Adequate waiting periods were maintained between load packages to ensure dissipation of excess pore water pressures developed during the previous load package.

The hollow steel monopile, of 80mm diameter and 2.5mm thickness (model scale), had a total length of 700mm and consisted of two segments: a 300mm segment, representing the foundation embedded in the soil, and a 400mm segment, representing a substructure extending between the seabed and the transition piece. In the upper section of the monopile, an additional cylinder was inserted in the monopile, to simulate the mass of the tower and the rotor blades - 1kg in model scale (corresponding to 216 tons in prototype scale), being representative of a 2MW to 2.3MW OWT. Figure 2 offers a schematic illustration of the experimental setup. The dimensions of the model in prototype scale are shown in Table 2.

Table 1. Characteristics of the centrifuge tests.

Test	**Type of lateral loading**	**Proto-type Period (s)**	**Dr (%)**	**Vis-cos-ity (cP)**
M2	Monotonic	-	85	wa-ter
C1	1way Sinusoidal	1	73	64
C2	1way Sinusoidal	1-3	76	65
C3	Random loading - Severe storm event	3-10	73	63

Table 2. Dimensions at prototype and model scale.

	Prototype	**Model Scale (1:60)**
Embeded Monopile length	18m	300mm
Substructure height	24m	400mm
Diameter	4.8m	80mm
Thickness	0.15m	2.5mm

During pluviation, the target relative density was set to D_r = 75%; the achieved D_r is summarized in Table 1. In the case of cyclic dynamic loading, the dense sand deposit was saturated using viscous fluid with 60 centipoise (cp) target viscosity, in order to allow for equivalent scaling of the excess pore water pressure generation and dissipation times.

Systematic numerical analyses were performed prior to testing to help design the test. These analyses used the Ta-Ger constitutive model for sand (Tasiopoulou & Gerolymos, 2016; Tasiopoulou et al., 2021), implemented in the finite difference software FLAC3D (Itasca, 2016), calibrated against published data on Ottawa sand, as demonstrated by Tasiopoulou et al. (2023). The numerical methodology that was followed herein is extensively described and validated (against the Takahashi et al., 2022 experiments) in Chaloulos et al. (2024). The numerical analyses: (1) helped identify the loading frequency range of interest; and (2) guided the instrumentation layout (Fig. 2), highlighting areas of interest in terms of deformations and excess pore water pressure development.

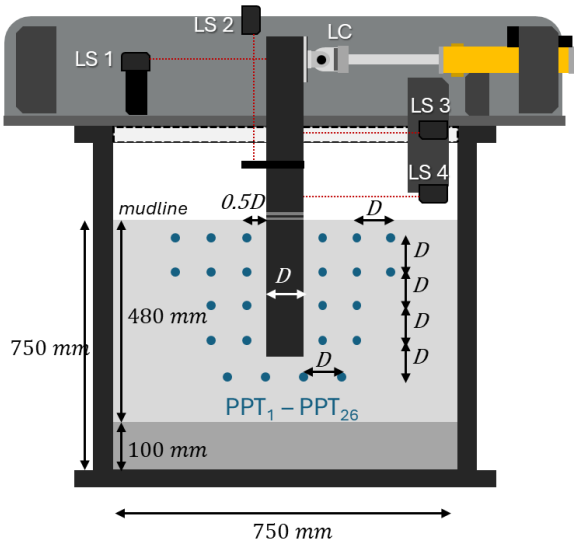

Figure 2. Overview of the experimental setup.

The embedded part of the monopile was instrumented with 10 pairs of strain gauges (SG), which capture the bending moment distribution. The (almost) rigid body movement of the substructure was monitored by 4 displacement Laser Sensors (LS). For the cyclic tests, 26 PPTs were carefully installed to record pore water pressure buildup, particularly in the vicinity of the monopile. A loadcell (LC) was mounted at the connection of the substructure with the dynamic actuator. At this connection, a sliding hinge was incorporated, combining a roller bearing with a linear slider. The connector allows the pile to settle or uplift freely during lateral loading, while isolating the loading arm from bending moment and shear loads, preventing errors and/or damage to the load cell.

2.3 Centrifuge Model Preparation Steps

Figure 3 illustrates the model preparation. Initially, a 100mm thick, gravel filter layer was placed at the bottom of the strong box. Subsequently, the sand was prepared stepwise in 5 layers, using the curtain-type air pluviation system. Layer interfaces coincide with the target depth of the PPT sensors. The aperture of the hopper, the drop height, and the passage velocity were calibrated specifically for Ottawa sand, to achieve the target 75% relative density. After the completion of each layer, the PPT sensors were carefully installed. Their exact position and the surface of each sand layer were surveyed, and the model was weighed prior to placing the subsequent layer. The resulting estimates of density per layer confirmed a relatively consistent and repeatable relative density. After completion of the pluviation to the "seabed" level, the sand surface was vacuum levelled with a controlled-guided system.

Following pluviation, the model was saturated with viscous fluid. A high degree of saturation (>99.8%) was critical, since partial saturation can significantly impact pore-pressure generation and the associated partial drainage response. Following the guidelines of Kutter et al. (2020), prior to saturation the model was flushed twice with CO_2, aiming to replace 98% of air with CO_2. Subsequently, de-aired viscous fluid was introduced to the specimen while an equal vacuum (80kPa) was applied both to the model and the fluid container. The flow of the viscous fluid to the model is controlled and driven by a low (and adjustable) differential head. Once the fluid free-surface reached the desired level (50mm above "seabed"), the flow was stopped and the degree of saturation verified using the method of Okamura & Inoue (2012).

After model saturation, the box was transported by a gantry crane and lowered onto the centrifuge swing. The monopile was then inserted by slow monotonic jacking using a manual hydraulic jack. Appropriate temporary support was employed to ensure correct alignment of the model pile during installation. The process was monitored using laser sensors, a load cell, and PPTs. Once the target penetration was reached, the guides were removed along with the 1g jacking loading frame. Finally, the actuator was slowly moved to the starting position and the sliding hinged connection was established by adding a pin between the hinges (roller bearings), on the actuator and the model. The model was then spun to the target g-level, and the loading sequences were applied. All stages (1g Jacking, Spin up, Testing, Spin down) were monitored and the results of all sensors recorded at a 2.5kHz sampling rate.

3 PRELIMINARY RESULTS

Selected results of the centrifuge model tests are presented in this section to preliminarily illustrate the observed mechanisms. To reveal qualitative trends in the results, the horizontal loads are presented in a normalized manner. Prior to testing, a few "blind" numerical predictions were made by GR8GEO for the as-designed model, and selected load sets were provided to ETHZ. Wherever available, these results are compared with numerical predictions performed prior to testing.

Figure 3 Stages of model preparation: (1,2) Pluviation and PPT placement; (3) saturation; (4) 1g jacking; (5) connection with the actuator before spin-up.

3.1 Monotonic Loading

As depicted in Figure 4, a hardening type of monotonic load-displacement response was observed in test M2. The lateral load in this figure is normalized to the load level in the test, at which the monopile lateral seabed displacement is 10% of its diameter, *D*. The blind numerical prediction shows a very similar trend, both qualitatively and quantitatively. During the monotonic test, where intermediate unloading was performed, a relatively stiff reloading response was observed until the virgin load curve was reached.

3.2 Constant-Amplitude Sinusoidal Loading

The loading sequence for cyclic tests C1 and C2 comprised sinusoidal constant-amplitude and constant-period loading packages of increasing intensity. Figure 5a depicts the incrementally increasing-amplitude load packages applied in test C1, conducted at a relatively short prototype period of 1 second, together with the resulting monopile rotation. The loads are given as a percentage of the maximum load, F_{max}, applied in the last package. For the first three load packages, the rotations tend to a constant rate of accumulation. In the fourth load package, the rotations abruptly increase, indicative of failure. This failure is attributed to liquefaction (excess pore water pressure ratio, $R_{u,max}$>0.7) of the soil around the upper part of the monopile, and mainly in front of the monopile relative to the loading direction, as illustrated in Figure 5b by the contours of maximum excess pore water pressure ratio, $R_{u,max}$, recorded by the PPTs during the last load package.

3.3 Irregular-Amplitude Storm Loading

The loading sequence for test C3 consists of realistic irregular-amplitude 10min windows from peak storm conditions, with a prototype period range between 6 and 10 sec. Four loading packages of increasing intensity are shown in Fig. 6a, together with the resulting monopile rotations. Within each package, the accumulated rotation increases with increasing load intensity. Figure 6b compares the blind numerical predictions to the centrifuge test results for the 4th load package (80%F_{max}) in terms of monopile load-rotation response, and excess pore pressure ratio, R_u, time histories. Taken from the transducer close to the seabed and behind the pile (relative to the loading direction), the R_u time history shows a tendency for negative excess pore water pressure development at the time of the peak load application. As with the monotonic tests, a very good comparison is observed between the trends of the blind predictions and the experimental results.

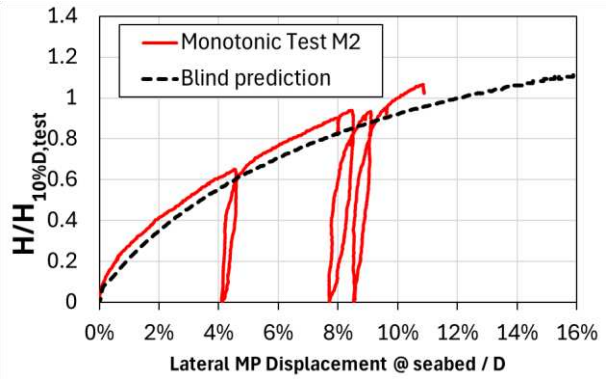

Figure 4. Comparison of blind numerical prediction (prior to testing) to the centrifuge test results: normalized horizontal load-monopile displacement response.

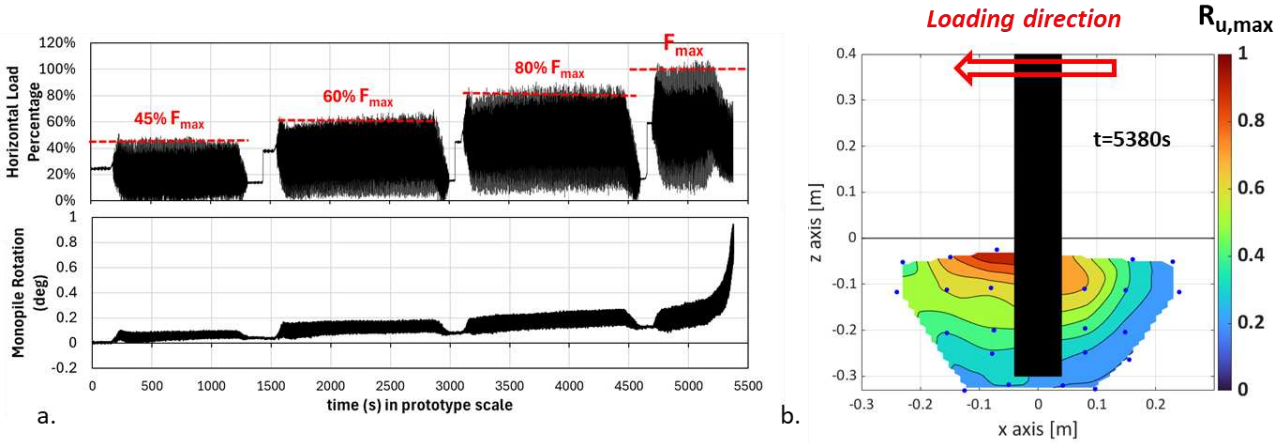

Figure 5. (a) Normalized cyclic sinusoidal loading sequence of test C1 and developed monopile rotation; (b) contours of maximum excess pore water pressure ratio, $R_{u,max}$, recorded in the maximum load package, F_{max}, based on PPT measurements.

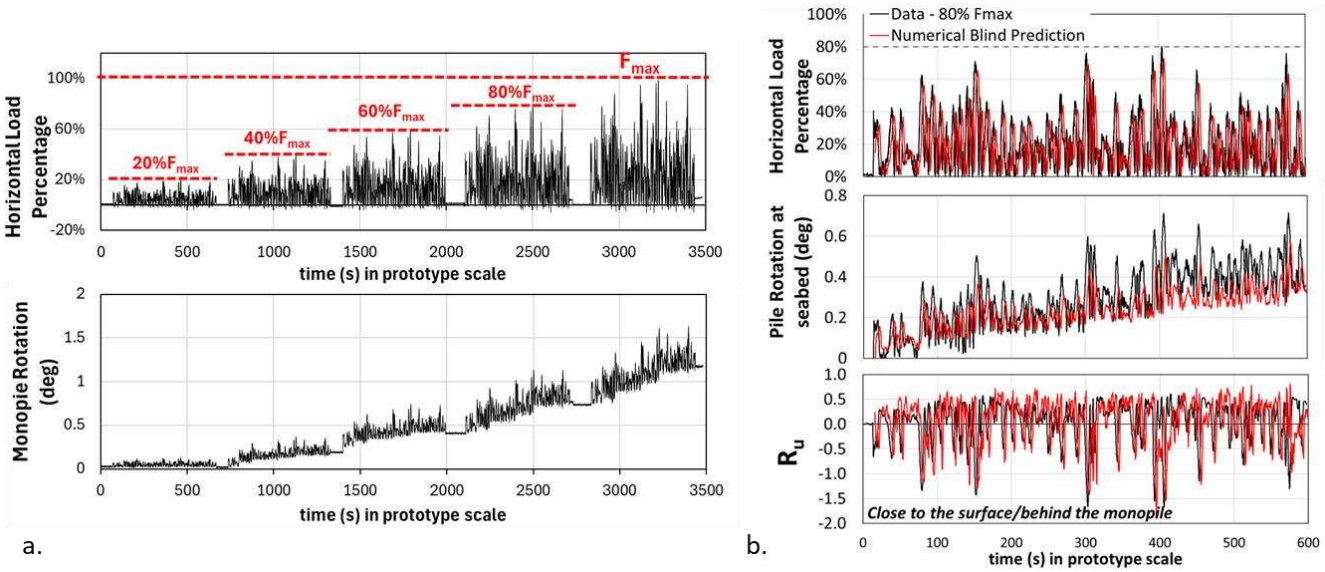

Figure 6 a. Normalized cyclic irregular loading sequence of test C3 and developed monopile rotation, b. comparison between centrifuge test data and blind numerical predictions for the 4th load package (80%F_{max}).

4 CONCLUSIONS

This paper presented novel centrifuge experiments of an OWT monopile foundation in saturated sand, subjected to load-controlled, cyclic dynamic loading. A newly developed dynamic actuator permitted a first-of-its-kind application of realistic storm loading time-histories to an OWT-monopile foundation, in addition to sinusoidal constant-amplitude time histories of varying frequencies. The availability of a large strong box facilitated detailed instrumentation, ensuring robust documentation of deformation and failure mechanisms of the OWT-monopile system, which is greatly affected by drainage conditions. This experimental dataset will serve as a valid and thorough base case for validation of state-of-the-art numerical tools, such as those used for blind predictions in this study. Even these early findings show that the Ta-Ger constitutive model can capture the most relevant mechanisms of the problem, indicating a promising avenue for design applications.

AUTHOR CONTRIBUTION STATEMENT

P. Tasiopoulou: Visualization, Conceptualization, Methodology, Writing- Original draft. **T. Limnaiou**: Software, Formal Analysis. **L. Sakeralliadis**: Data Curation, Writing, Methodology **J. Chacko**: Conceptualization**,** Reviewing and Editing, **L. A. Jones, A. Agalianos, I. Anastasopoulos**: Visualization, Data Curation, Reviewing and Editing.

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