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Capturing the effect of installation induced locked-in stresses on the lateral behaviour of monopiles through centrifuge testing

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ABSTRACT: Monopiles remain the cornerstone foundation solution for fixed offshore wind turbines, valued for their cost-effectiveness and reliability. However, the accuracy of current design practices, which predominantly rely on wished-in-place calculations, is limited by their inability to capture critical installation effects – such as stress state and density changes in the surrounding soil during pile driving. Although these effects are recognised as key factors that influence lateral capacity and stiffness, they remain difficult to quantify. Centrifuge modelling is a powerful tool that enables controlled, repeatable, and cost-effective testing of complex soil-structure interaction problems, which can often be impractical or prohibitively expensive to replicate in the field. However, testing may fail to capture the true installation effect in cases where the centrifuge is stopped between pile installation and lateral loading stages, as this will release any locked in stress that may be generated during driving. This limitation has the potential to undermine the value of data from centrifuge model scale experiments, as they can misrepresent the true in situ behaviour of monopiles. To address this challenge, novel apparatus has been developed at the University of Western Australia that allows for in-flight pile driving and two-way lateral loading without needing to stop the centrifuge. This ensures any change in soil stress state and density due to pile installation can be preserved, providing a more accurate representation of field conditions. Preliminary results highlight a significantly stiffer and stronger response in tests conducted entirely in-flight, compared to those where the centrifuge was temporarily stopped. This finding not only challenges conventional centrifuge modelling practices, but also reinforces the importance of capturing installation effects in pile behaviour studies.

KEYWORDS: Monopiles, Centrifuge Modelling, Lateral load.

1 INTRODUCTION

The technique of geotechnical centrifuge modelling is a well-established means of reliably modelling the behaviour of geotechnical materials at small scale. The strength and stiffness of soil are governed by the effective stress, so small scale models conducted at unit gravity (1g) do not capture the correct behaviour. If a small-scale model is accelerated within a centrifuge, the self-weight of the soil is enhanced by the ratio of the centrifuge acceleration to Earth's gravity. This ratio is denoted N and is the scaling factor that is used to scale the dimensions of the centrifuge model relative to field conditions. The main scaling laws relevant to this paper are summarised in Table 1. General descriptions of centrifuge modelling and the associated scaling principles are reported in numerous publications, such as Schofield (1980) and Garnier et al. (2007).

Table 1. Scaling laws for centrifuge modelling

Parameter	Dimension	Scaling relationship
Acceleration	$[LT^{-2}]$	N
Length	[L]	1/N
Area	$[L^2]$	$1/N^2$
Volume	$[L^3]$	$1/N^3$
Force	$[MLT^{-2}]$	$1/N^2$
Stress	$[ML^{-1}T^{-2}]$	1
Strain	-	1
Mass	[M]	$1/N^3$
Density	$[ML^{-3}]$	1
Velocity (dynamic)	$[LT^{-1}]$	N
Time (consolidation)	[T]	$1/N^2$

Monopile lateral response has been widely investigated through centrifuge modelling, which in most cases employed jacked installation at 1g followed by in-flight loading. However, the installation method is known to significantly alter the surrounding soil state, potentially affecting the lateral capacity mobilisation response. Although the influence of installation on axial capacity is well established (De Nicola and Randolph, 1997, Henke and Bienen, 2013), its impact on lateral response remains an active area of research. Piles installed in-flight tend to exhibit a stiffer load-displacement response and higher capacity than piles installed at 1g (Dyson and Randolph, 2001; Klinkvort et al., 2013). However, these previous studies involved a period where the centrifuge was stopped after in-flight installation to set up for lateral loading. Fan et al. (2021) showed that piles installed and laterally loaded in-flight without stopping the centrifuge resulted in 2.4 times the initial stiffness and 30% higher capacity than piles installed at 1g and subsequently loaded in-flight, clearly showing that in-flight installation is important. However, the effect of stopping the centrifuge after installation to set up for lateral loading has never been directly addressed. This paper presents new test data that compares the lateral behaviour of a pile installed and loaded in-flight (without stopping the centrifuge) with a case where the pile was installed in-flight, but lateral loading was applied only after a centrifuge spin down/up cycle. These results are part of broader research efforts aimed at investigating the effects of different installation techniques on the monotonic response, initial stiffness, and two-way cyclic response of monopiles (and other foundation systems).

2 CENTRIFUGE MODELLING

A series of monopile tests were carried out using the 10 m diameter beam centrifuge at the National Geotechnical Centrifuge Facility at University of Western Australia (Figure 1). This centrifuge, an Actidyn C72-2 model rated at 240 g-tonnes, features a fixed beam design with a 1.2 × 1.2 × 1.2 m platform capable of carrying 2400 kg at 100g (133.7 rpm) or 1400 kg at its peak acceleration of 130g (152.5 rpm). Further details of the centrifuge, commissioned in 2016, are available in Gaudin et al. (2018). The monopile tests were performed in a single silica sand sample, prepared by dry pluviation into a rectangular 'strongbox' (1000 mm × 1000 mm × 500 mm) before saturating the sample with water from the strongbox base.

The two tests considered in this paper explore the influence of stopping the centrifuge between installation and lateral loading on pile capacity and stiffness, and are part of a broader study that investigates the effect of varying centrifuge procedures on the response of different foundation types. All tests were conducted at 80g.

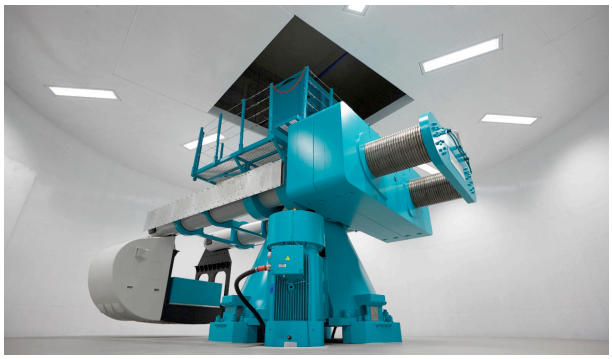

Figure 1. The 10 m diameter beam centrifuge at UWA

2.1 *Soil sample preparation and properties*

The properties of the silica sand used in the tests are detailed in Table 2. The material is a fine, poorly graded, sub-angular sand with grains ranging from sub-rounded to sub-granular. The sample was saturated inflight from the strongbox base at an acceleration of 30g, which allows for faster saturation without the risk of piping due to the higher effective stresses (relative to a 1g saturation). Several centrifuge 'conditioning ramps' — cycling from 1g up to the testing acceleration of 80g — were performed in an attempt to bring the sample to an equilibrium density state before testing. Measurements of mass and volume following these conditioning ramps indicated a relative density of approximately 90%.

Table 2. Index properties of UWA silica sand

Parameter	Value
Specific gravity, G_s	2.67
Particle size, d_{10}, d_{50}, d_{60}	0.12, 0.18, 0.19 mm
Dry density, ρ_d	1740 kg/m^3
Minimum dry density, ρ_{min}	1497 kg/m^3
Maximum dry density, ρ_{max}	1774 kg/m^3
Constant volume friction angle, φ_{cv}	31.9° (triaxial)

The sample was characterised using cone penetrometer tests (CPTs) conducted in-flight across the testing area, both prior to any pile tests and after the pile tests were complete. Depth profiles of cone tip resistance, q_c, are presented in Figure 2, which indicate minimal spatial variability across the sample and no significant densification during the test campaign. The profiles shown in Figure 2 have been corrected for scale effects, following the approach of Lehane et al. (2023), to represent an equivalent field-scale cone penetrometer response.

2.2 *Pile model*

The model piles were fabricated from 50 mm diameter titanium tube with a wall thickness of 1 mm, such that the diameter to wall thickness ratio, $D/t = 50$. At the testing acceleration of 80g this model represents a field scale pile with a diameter, $D = 4.0$ m and wall thickness, $t = 80$ mm. The titanium is grade 2, which has a density, $\rho = 4500$ kg/m^3, Young's modulus, $E = 105$ GPa, and yield strength, $f_y = 275$ MPa at 0.2% offset elongation. The tests presented in this paper utilised piles that were embedded by $L = 150$ mm ($L/D = 3$), and with a load application point 500 mm (10D) above the mudline, such that the overall length was 650 mm. The surface of the model piles (external and internal) was sand blasted, which resulted in an average roughness, $R_a = 4$ µm, as measured using a stylus profilometer.

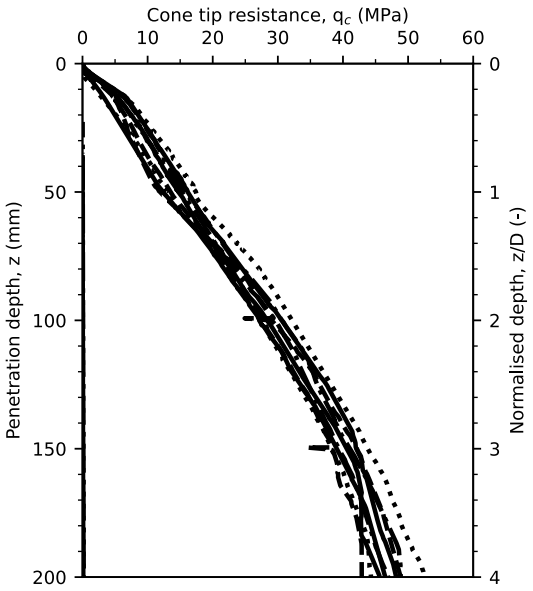

Figure 2. Depth profile of cone tip resistance, q_c

2.3 *Pile installation*

The piles were installed using a model scale pile hammer that is capable of in-flight driving of piles into very strong samples (Nietiedt et al. 2023a). The experimental arrangement using this hammer is shown in Figure 3. The hammer consists of a 0.1 kg ram that is lifted by a double cam and bearing system, actuated by a rotary motor, so that it free-falls from a maximum height of 20 mm (1.6 m in prototype scale at 80g) before being picked up by the cams again. The ram, made of a solid hardened stainless-steel rod to which the bearings are attached, is held in position by rollers that permit only vertical movement with minimal friction. At an acceleration of 80g, the hammer has a potential energy of 2.8 J and can operate at a frequency of up to 4 Hz, with a blow velocity of 5.6 m/s, modelling (at field scale) approximately 1480 kJ of energy at a frequency of 0.05 Hz and a blow velocity of 5.6 m/s. The driving system is mounted on the vertical axis of a 2-directional electro-mechanical actuator, which is programmed to follow the pile penetration, maintaining a constant drop height through the use of the software feedback loop with the feedback provided by a linear displacement transducer that measures displacements of the pile. Drop heights, and therefore the energy, can be varied during a test by moving the actuator up or down while the pile is stationary. A complete description of the hammer can be found in Nietiedt et al. (2023a). As shown in Figure 3, the hammer impacted a stainless steel pile cap attached to the top of the pile, which transmitted the hammer energy to the pile during driving.

2.4 *Two-way loading apparatus*

A novel apparatus was designed and developed such that two-way lateral cyclic loading could be applied to the monopile installation without stopping the centrifuge. The apparatus is also shown in Figure 3, with further details presented in Figure 4. It consists of a rail located at the top of the pile that allows the actuator to impose horizontal motions on the pile, with rollers in the rail providing vertical 'freedom' between the

vertical axis of the actuator and the pile. During installation the actuator moves vertically downward to match the pile embedment, while the rail remains connected with the rollers for lateral stability as in Figure 4. When the pile is fully installed the actuator is moved upward by an amount that frees the hammer off the pile head. Lateral motions can then be applied to the pile by operating the horizontal axis of the actuator, with the amplitude of motion controlled by displacement measurements. Alternatively the horizontal axis of the actuator can be operated in load control, using the feedback from the load cell used to measure the lateral load that develops at the load application point (see Figure 3 and Figure 4). This apparatus allows for combinations of monotonic loading, one- and two-way cyclic loading (under displacement or load control) and pluck tests (to measure pile-soil natural frequency) to be carried out without spinning down the centrifuge.

Lateral loads were measured using a horizontally orientated load cell (see Figure 3 and Figure 4) located on the vertical axis of the actuator. Pile head movement and rotation were determined from a combination of laser displacement sensors and linear displacement sensors (at different elevations on the pile). UWA experience from previous testing campaigns is that this provides sufficient information for both pile head displacement and rotation to be established, noting that other sensors (such as tilt meters) may not survive the high energy imparted during pile driving.

Although not utilised in the analysis reported in this paper, the piles were instrumented with two pairs (for redundancy) of fibre optic strands along the internal walls of the pile, attached to opposite sides such that (during lateral loading) one pair measures compressive strain while the other measures tensile strain. This particular measurement system provides strain measurements with a spatial resolution of 3.3 mm down the pile length, which allows for quasi-continuous measurement of strain along the length of the pile without the instrumentation bulk associated with use of conventional foil-based strain gauges. Details of the fibre optic measurement system used at the NGCF are described in Guevara et al. (2022).

3 RESULTS AND DISCUSSIONS

The effect of stopping the centrifuge between installation and lateral loading is explored in this paper by comparing two tests: i) an 'in-flight' test, in which a 650 mm long pile was impact driven 150 mm (3*D*) into the sand and subsequently loaded monotonically at an elevation of 500 mm (10*D*) above the sand surface, all in-flight without spinning down the centrifuge; and ii) a 'ramp-down' test, in which the same pile was similarly impact driven in-flight, but only loaded after stopping the centrifuge and then spinning back up to 80g. Each test was conducted at an undisturbed location in the sample.

3.1 *Pile driving records*

In terms of installation, no differences should be expected between the 'in-flight' and the 'ramp-down' tests, as both followed the same procedure. The two tests started with an initial 25 mm self-weight embedment at 1g, which ensured pile verticality during centrifuge ramp up. Further self-weight penetration occurred as the centrifuge acceleration increased to 80g, with final self-weight embedment in the range 30 - 35 mm. Shortly after the centrifuge acceleration reached 80g, pile driving commenced. Figure 5 shows depth profiles of the cumulative number of hammer blows required for each test. Reasonably good agreement between tests was achieved, with the test that was subsequently subjected to a centrifuge stop requiring only slightly more (19% more) blows to reach the target depth.

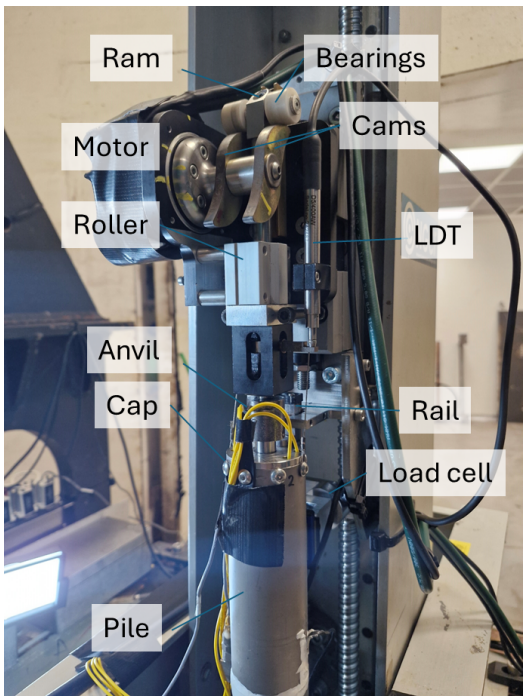

Figure 3. Pile installation and lateral loading set up

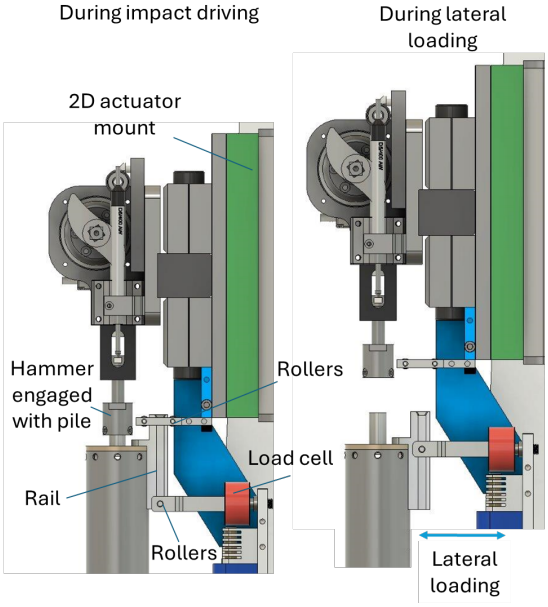

Figure 4. Apparatus configuration during driving and lateral loading

3.2 *Effect of centrifuge spin-down on monotonic lateral loading response*

The effect of stopping the centrifuge between installation and pile loading is shown in Figure 6, which compares the capacity mobilization response for both tests. Figure 6 clearly shows that the in-flight test not only resulted in 18% higher capacity, i.e. from 410 to 485 N (2.6 to 3.1 MN in prototype scale) at a normalised mudline displacement, d/D of ~ 4.0%, but also in a 20% higher initial secant stiffness (for a mudline displacement, d/D = 0.5%), i.e. from 548 to 660 N/mm (44 to 53 MN/m in prototype scale). As the sand was already in a dense and stable state before installation, with D_r = 90% after conditioning spins, and both tests involved similar in-flight impact driving, it is unlikely that the difference is due to sample densification and grain crushing differences. Rather, stopping the centrifuge is likely to have released any locked-in stresses from driving that not only affected the stiffness but also the pile capacity.

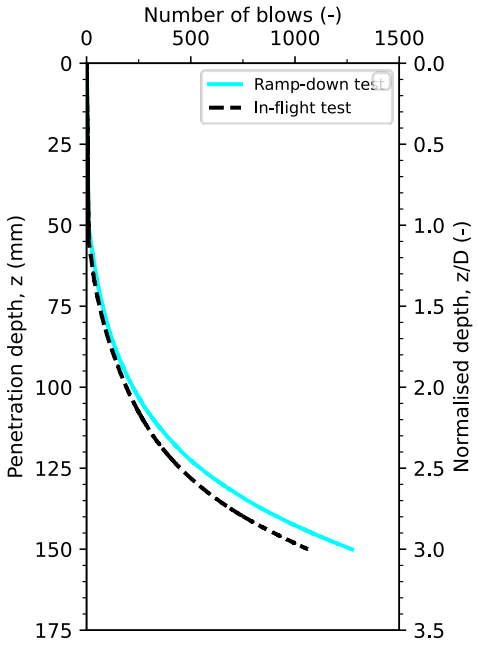

Figure 5. Cumulative blows to install the piles

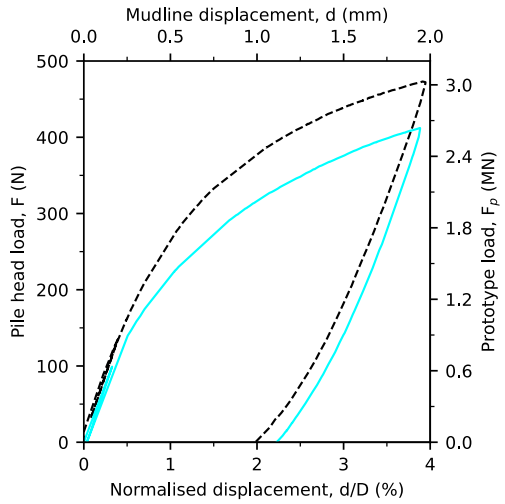

Figure 6. Pile head load vs pile head displacement for the in-flight and ramp-down tests

4 CONCLUSIONS

This paper presents a direct comparison between two centrifuge model tests: one in which the pile was both installed and laterally loaded entirely in-flight, and another where lateral loading followed a centrifuge spin down/up cycle after installation. These tests, which are part of a broader research program investigating the effect of centrifuge test procedures on observed foundation response (including for monopiles), were made possible through the use of a custom two-way loading apparatus designed to apply lateral loads in-flight, eliminating the need to stop the centrifuge between different stages of the test. The results revealed that the test conducted fully in-flight exhibited a 20% stiffer response and 18% higher capacity relative to the test that involved a centrifuge spin down/up cycle. While previous work has shown that wished-in-place conditions or a 1g installation followed by centrifuge lateral loading do not produce realistic pile behaviour, the results presented here demonstrate that in-flight installation alone is not sufficient. Preserving in-flight stresses generated during the installation phase are important for the lateral loading phase to be modelled correctly, which challenges common centrifuge modelling practices that stop the centrifuge between these phases. Further research should investigate how different installation techniques influence the lateral response across a range of soil types and densities, particularly where grain crushing and installation-induced densification may play a significant role.

5 ACKNOWLEDGEMENTS?

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