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Lateral loading of in-flight vibratory-driven and impact-driven piles in sand within a geo-centrifuge

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ABSTRACT: Vibratory driving is emerging as a promising alternative to traditional impact driving for offshore monopile installation. It offers significant advantages, including reduced noise emissions, mitigation of pile-run risks, and faster installation. In practice, the primary concern when considering vibratory installation is whether piles can be reliably driven to target depth under varying ground conditions. Beyond drivability, however, broader adoption also depends on a clear understanding of how this installation technique influences the in-service performance of the foundation, particularly its lateral behaviour, which governs dynamic response, lateral capacity, and cyclic accumulation (ratcheting) in offshore wind applications.To address this knowledge gap, the lateral response of model piles in sand installed in-flight using vibratory or impact methods is investigated in TU Delft geo-centrifuge. This work, conducted within the SAGE-SAND and GEOLAB FoundEx projects, integrates a custom-built vibratory driver developed at UCLouvain with impact hammering and lateral loading systems designed at TU Delft. The experimental campaign examines the monotonic and cyclic lateral behaviour of piles installed under controlled conditions, enabling a direct comparison of the effects of installation methods on pile performance. The results offer new insights into the role of installation techniques on soil-structure interaction and provide valuable data to support more reliable and environmentally favourable foundation design strategies for offshore wind turbines.

1 INTRODUCTION

Vibratory driving is increasingly considered as an alternative to conventional impact driving for the installation of offshore wind monopiles, driven by its potential to reduce underwater noise, reduce installation time, and mitigate risks associated with pile run (Bailey 2010; INNWIND.EU Consortium 2015; Molenkamp 2025). Recent research has focused on the understanding of vibro-driveability (Holeyman *et al.* 2020; Tsetas *et al.* 2023; Mazutti *et al.* 2025, 2026; Simonin *et al.* 2025), as well as the effects of vibratory installation on the post-installation lateral behaviour of monopiles, which governs offshore foundation performance.

For offshore wind turbines, lateral stiffness, cyclic degradation, accumulated displacements (ratcheting), and post-cyclic capacity are critical design aspects, controlling both ultimate and serviceability limit states (Sunday and Brennan 2021). These aspects are strongly influenced by the installation process, through changes in stress state, density, and soil fabric. Impact driving is known to induce significant soil densification and stress redistribution, whereas vibratory driving may lead to different disturbance mechanisms, including soil rearrangement or partial fluidisation of the surrounding soil (Rodger and Littlejohn 1980; Staubach *et al.* 2022).

Experimental studies addressing the lateral behaviour of vibratory-driven piles remain limited. Available laboratory and centrifuge investigations often focus on post-installed piles or lack direct comparison with impact-driven reference cases under comparable stress conditions (Fan et *al.* 2021; Peccin da Silva *et al.* 2023). Likewise, few medium-scale field studies address this difference (Achmus *et al.* 2020; Kementzetzidis *et al*. 2023; Simonin *et al.* 2026). As a result, uncertainties persist regarding whether vibro-driven piles exhibit comparable lateral stiffness, cyclic degradation, and ratcheting behaviour to impact-driven piles.

This paper presents the preliminary results of a dedicated centrifuge test campaign conducted at TU Delft, in which model piles were installed in-flight in dense sand using either vibratory or impact driving, and subsequently subjected to monotonic and cyclic lateral loading, also compared to hand-driven piles at 1g. By combining a newly developed miniature vibro-driver (Simonin *et al.* 2024; Simonin *et al.* 2025) with dedicated impact and lateral loading systems, the study enables a controlled comparison of the influence of installation technique on lateral pile behaviour. The results provide new experimental evidence to support the assessment of vibratory driving as a viable installation method for offshore monopiles.

2 METHODOLOGY

2.1 Centrifuge modelling

Geotechnical centrifuge modelling enables the investigation of soil–structure interaction at representative stress levels by subjecting a reduced-scale physical model to an elevated acceleration field. By increasing the gravitational acceleration by a factor *N*, stresses induced by self-weight in the model replicate those occurring in the corresponding full-scale prototype, allowing realistic simulation of geotechnical behaviour within a controlled laboratory environment. Interpretation of centrifuge test results relies on established similitude principles, which define consistent scaling relationships between model and prototype quantities (Garnier *et al*. 2007).

In this study, experiments were performed at an acceleration level of 50g (N = 50) to ensure representative stress conditions for monopile installation and subsequent lateral loading in dense sand. The scaling laws governing pile geometry, driving forces, vibratory and impact driving characteristics, and lateral loading are summarised in Table 1.

Particular attention was paid to the scaling of vibratory driving parameters, for which both frequency and eccentric moment must be adjusted to achieve realistic inertial forces at model scale, and impact driving, where a miniature ram mass and a very short stroke must be used. Detailed discussions on scaling strategies for vibratory pile installation can be found in Mazutti *et al.* (2022). These scaling principles form the basis for the design and operation of the miniature vibro-driver and impact hammer used in the present centrifuge campaign.

Table 1. Scaling laws.

Quantity	Scaling factor
Acceleration (e.g. centrifugal, vibrational)	N
Length (e.g. pile diameter, length, wall thickness, ram stroke)	1/N
Density (e.g. soil, pile material)	1
Time	1/N
Frequency (e.g. vibration)	N
Mass (e.g. ram mass)	$1/N^3$
Stress (e.g. in the soil and pile)	1
Strain	1
Force (e.g. lateral loading, impact and vibration forces)	$1/N^2$
Energy (e.g. blow energy)	$1/N^3$

2.2 Sample preparation and pile geometry

295 mm diameter and 160 mm deep samples of dry Geba sand (see Beroya-Eitner *et al.* (2022) for characteristics) with relative density of 80% were prepared by hand pluviation, shock-wave compaction and final vibration. The diameter of the sample has led to the selection of a 25 mm diameter open-ended hollow stainless-steel pile to avoid boundary effects upon lateral loading and driving. The pile has a wall thickness of 0.5 mm, leading to a diameter to wall thickness ratio of 50, which is inferior to offshore monopiles (with a range of 60 to 120) but constrained by the availability of thin wall tubes. The 210 mm long pile is driven 75 mm within the sample, leading to an embedment-to-diameter ratio of three comparable to that used in medium-scale field tests (e.g., McAdam *et al.,* 2019), allowing future comparisons. Importantly, the corresponding prototype diameter of this pile is 1.25 m. This limits direct comparison to offshore monopiles (typically 6 to 10 m in diameter) which behaviour could differ due to size effects.

2.3 Miniature vibro-driver

Vibratory installation was performed using an updated miniature vibro-driver developed at UCLouvain and operated in TU Delft’s geotechnical centrifuge, following the principles described in Simonin *et al.* (2024, 2025). The device reproduces the working principle of offshore vibro-hammers by means of pairs of counter-rotating eccentric masses generating a sinusoidal vertical driving force. For centrifuge tests conducted at 50g, a vibrating frequency of 1 kHz was adopted, corresponding to a prototype frequency of approximately 20 Hz representative of vibro-drivers used offshore.

In the present study, all vibratory installations were carried out using a total eccentric moment of 4 g.mm, equivalent to 25 kg.m at prototype scale. The vibro-driver was equipped with an upgraded high-speed brushless ECXSPEED 16L motor, capable of activating eccentric moments of 16 g.mm at frequencies exceeding 1 kHz. The eccentric masses and motor were mounted on a platform rigidly fixed to the pile head and guided by linear shafts to ensure verticality during driving. The pile-vibro-driver system comes out of these linear shafts before reaching its embedment depth, allowing the subsequent lateral loading.

The combined mass of the pile–platform system was 430 g at model scale, corresponding to approximately 54 t at prototype scale. A counterweight–spring system was used to reduce the effective static driving weight to 36 N at model scale, yielding a representative pile–hammer weight while accounting for motion through the centrifuge acceleration field. Further details of the vibro-driver design and operating principles are provided in Simonin *et al.* (2024).

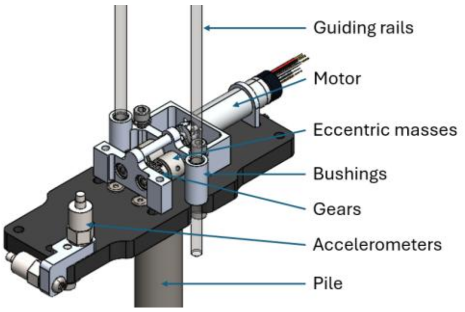

Figure 1. Updated miniature vibro-driver

Figure 2 presents the evolution of the embedment with time for the three vibratory-driven piles, demonstrating the repeatability of the vibratory driving process. The target depth is reached after 40 s to 75 s at model scale, corresponding to 30 min to 1 h at prototype scale.

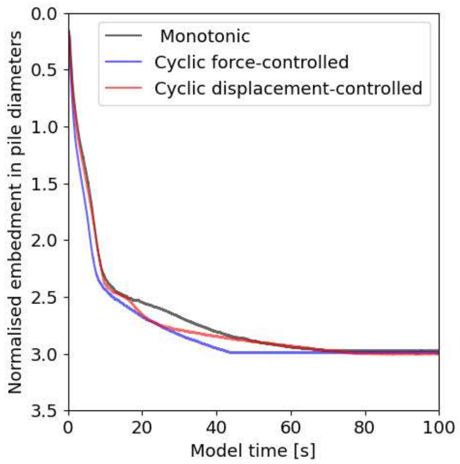

Figure 2. Normalised penetration of the vibratory-driven piles against time

2.4 Miniature impact hammer

Impact-driven installation was performed using a miniature electro-mechanical pile driving actuator developed at TU Delft, following the principles described by Quinten *et al.* (2022) and pictured in Figure 3.

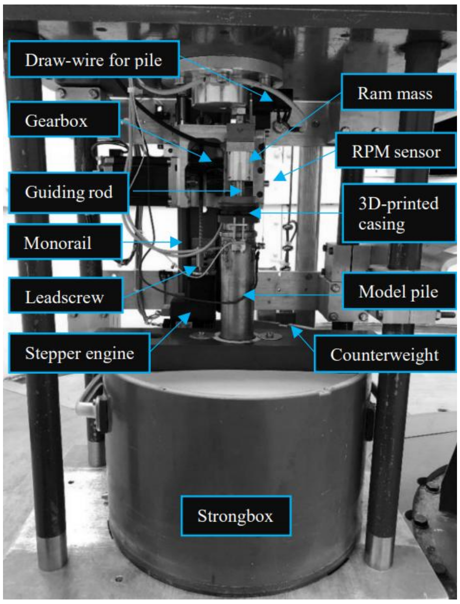

Figure 3. Miniature impact hammer (Quinten et al. 2022)

The device reproduces offshore hydro-hammer driving under centrifuge conditions by releasing a guided ram mass onto the pile head at controlled frequency and stroke. In the present study, a ram mass of 80 g and a stroke of 15 mm were used at 50g acceleration, corresponding at prototype scale to a 10 t ram mass, a 0.75 m stroke, and a blow energy of approximately 73 kJ. Driving was conducted at a model-scale frequency of 2 Hz, equivalent to 2.4 blows per minute at prototype scale. This is slower than in offshore practice, but enabled to control precisely the embedment depth. The actuator is mounted alongside the pile and tracks its penetration in real time using a PID-controlled positioning system, ensuring consistent impact conditions throughout installation.

Figure 4 presents the evolution of the embedment with time for the three impact-driven piles, also demonstrating the repeatability of the impact driving process. The target depth is reached after 43 s to 50 s in model time, corresponding to 36 min to 42 min in prototype time. The hammer is disproportionately large compared to the pile, which explains that only 86 to 100 blows were necessary to drive the pile to its target depth, compared to the typical offshore values (>1000 blows).

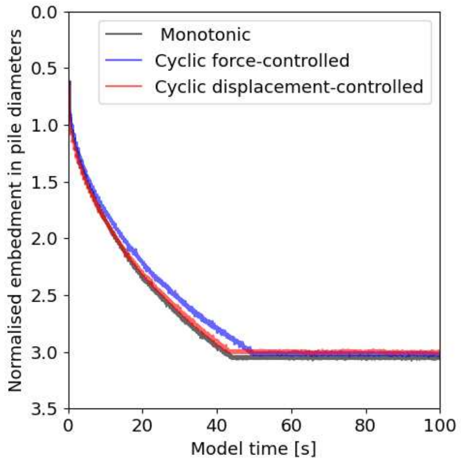

Figure 4. Normalised penetration of the impact-driven piles against model time

2.5 Lateral load actuator

Post-installation lateral loading was applied using the TU Delft centrifuge lateral loading actuator described by Orakci *et al.* (2024) pictured in Figure 5. The device is designed to operate at centrifuge accelerations up to 100g and provides a maximum lateral force of 5 kN. It integrates directly with the pile installation hardware, allowing lateral loading to be applied immediately after installation without stopping the centrifuge, thereby preserving the in-situ stress state around the pile. The actuator can operate in either load- or displacement-controlled modes and enables both monotonic and cyclic lateral loading at representative prototype frequencies.

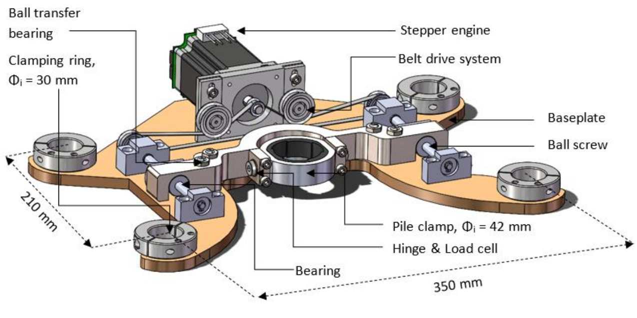

Figure 5. Rendered image of the TU Delft actuator

2.6 Reference tests

The pile-driver configuration differs between vibratory and impact driving and the subsequent loading phase. The vibro-driver is tightly secured to the pile to transmit vibrations effectively. Consequently, the lateral loading of in-flight vibro-driven pile is done on a pile where the vibro-driver is still present along with its counterweight system.

In comparison, the anvil of in-flight vibro-driven piles is smoothly removed in-flight before the lateral loading follows on the sole pile.

In consequence, tests on vibro-driven and impact-driven piles are not directly comparable. To circumvent this limitation, reference tests were done on piles hand-driven at 1g to the same three-diameter embedment both on the sole pile and on the pile-vibro-driver system. While this paper does not correct for the presence of the vibro-driver atop the pile, future efforts taking advantage of these reference tests will enable the direct comparison of vibro-driven and impact-driven piles.

3 RESULTS

3.1 Monotonic

Figure 6 and Figure 7 picture the lateral monotonic response under 50g of the model pile, with the lateral load measured by the load cells of the lateral loading actuator against the displacement measured by a laser aiming at the pile 25 mm -one pile diameter- above the mudline. The loading was applied at a 0.25 mm/s rate at the frame level, 65 mm above the mudline.

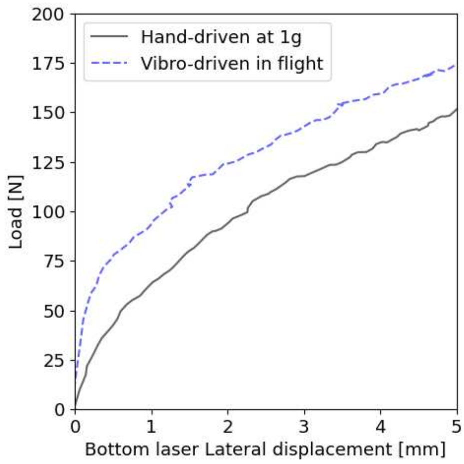

Figure 6. Monotonic lateral load tests on an in-flight vibro-driven pile and a hand-driven pile at 1g

Figure 6 depicts the lateral response of the pile capped by the vibro-driver for a hand-driven pile at 1g and an in-flight vibro-driven pile. The lateral response of the in-flight vibro-driven pile is initially stiffer and develops more resistance than the hand-driven pile.

Figure 7 depicts the lateral response of the sole pile for a hand-driven at 1g and an in-flight impact-driven pile. Again, the in-flight driven pile presents a stiffer and stronger response than the hand-driven pile at 1g.

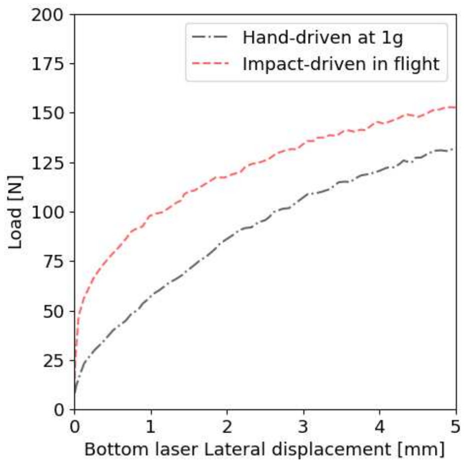

Figure 7. Monotonic lateral load tests on an in-flight impact-hammered pile and a hand-driven pile at 1g

Comparing the two figures, the two 1g driven piles, with or without the vibro-driver, exhibit close to identical initial stiffness and only a slightly larger capacity as displacement grows for the pile with the vibro-driver. The latter can be an artefact due to the contribution of the counterweight pulley system of the vibro-driver opposing resistance to the lateral loading. The exact same observation can be made for the impact and vibro-driven piles, which tend to show that the vibro-driven and impact-driven piles exhibit similar lateral behaviour. This observation is in contradiction with medium-scale field testing for vibro- and impact-driven piles such as in the SAGE-SAND project (Simonin *et al.,* 2026) where impact-driven piles exhibit a stiffer response as well as a larger ultimate capacity than vibro-driven piles. Besides the scales, other differences between these tests that should be considered are:

- The pile dimensions: the SAGE-SAND project used 2 m diameter piles, compared to 1.25 m at prototype scale here, with 25 to 40 mm wall thickness, compared to 25 mm here, and an embedment ratio of 8.5 diameters, compared to 3 here.
- The nature of the soil: the SAGE-SAND project piles are mainly founded in medium sand but other variety of soils are present such as fine sand, silt, peat (Letizia *et al*. 2024), while the experiments presented herein are on uniform fine sand.
- The sand density: based on the CPT characterisation of the site (Letizia *et al*. 2024), the piles are founded in looser sand with relative densities from 49% to 70%, compared to the 80% herein.
- The saturation of the soil: the centrifuge tests are on dry sand such that there is no liquefaction involved during the driving.
- The impact and vibratory hammers: the SAGE-SAND project made use of a S-200 IQ Hydrohammer, blows of 200 kJ compared to 73 kJ here, and a PVE-150M, involving an eccentric moment of 150 kg.m at a frequency of 23.3 Hz compared to the 25 kg.m and 20 Hz used here.

3.2 Two-way cyclic

Displacement-controlled cyclic tests were conducted with the displacement control done on a laser aiming at the pile 85 mm above the mudline. Three thirty-minute packets of 0.25 mm, 0.5 mm and 1 mm amplitudes were applied to the pile at a frequency of 0.5 Hz as pictured in Figure 8. Tests were conducted on a hand-driven at 1g pile capped by the vibro-driver, an in-flight vibro-driven pile, and an in-flight impact-driven pile, for which the lateral load responses are pictured against time in Figure 9, Figure 10, and Figure 11 respectively.

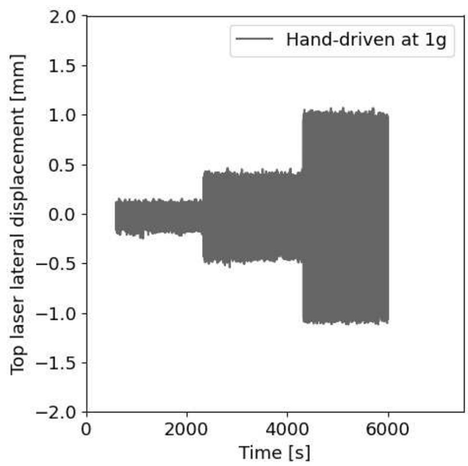

Figure 8. Displacement control signal for hand-driven pile

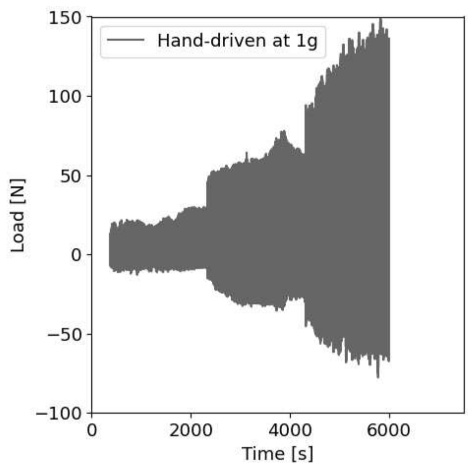

Figure 9. Cyclic lateral load tests on a hand-driven pile at 1g

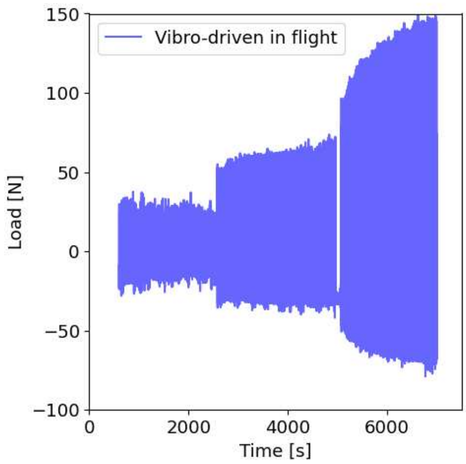

Figure 10. Cyclic lateral load test on an in-flight vibro-driven pile

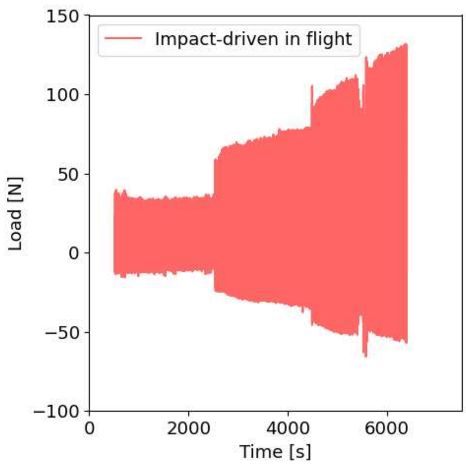

Figure 11. Cyclic lateral load test on an in-flight impact-driven pile

During the first load-packet, the in-flight driven tests exhibit cycles of approximately constant load amplitude throughout, with an amplitude of 25.5 N for the vibro-driven pile, and 23 N for the impact driven pile. The hand-driven pile exhibits a hardening from 13.5 N to 16 N, these lower values reflecting the softer initial response of the hand-driven monotonic response compared to the in-flight driven piles.

During the second load-packet, all tests exhibit hardening, from 32 N to 47 N for the hand driven pile, from 42 N to 50 N for the vibro-driven pile, and from 39 N to 56 N for the impact-driven pile. This indicates that the hand-driven pile at 1g converges to the same level of lateral resistance as the in-flight driven piles after 2000 cycles.

During the third load-packet, the impact driven pile, which is the only one not capped by the vibro-driver, exhibits a smaller amplitude than the both hand-driven and vibro-driven piles. Comparing the amplitudes of the hand-driven pile at 1g with the in-flight vibro-driven pile, both initial (~50 N) and final (~90 N) amplitudes are similar. While the monotonic capacity of the in-flight vibro-driven pile is larger than the hand-driven pile at 1g, cyclic loading appears to have leveled the difference in capacity at this displacement range for the two installation techniques.

4 DISCUSSION

The results demonstrate that piles installed in-flight under centrifuge conditions exhibit a noticeably stiffer initial lateral response and higher lateral resistance than otherwise identical piles installed by hand at 1g. This observation is consistent with centrifuge studies showing that installation at elevated stress levels induces soil densification and stress history effects that are preserved around the pile and lead to enhanced lateral capacity compared to piles installed at 1g. For example Li *et al.* (2025) observe an 11% increase in capacity for piles installed at 50g compared to piles installed at 1g, while here it seems to be in the order of 25%. Such findings underline the importance of accounting for installation stress state when interpreting centrifuge lateral load tests.

Peccin da Silva *et al.* (2025) observed experimentally that impact driven piles demonstrated stiffer response and a larger capacity than vibro-driven piles. Numerically, they showed that taking into account installation effects, such as increased horizontal stress due to the impact driving, were essential to capture the lateral behaviour of impact driven piles, while vibro-driven were more readily modelled as wished in place piles. The results of the experimental campaign presented in this paper diverge from these conclusions, showing that both impact and vibro-driven piles have a stiffer response and more lateral resistance than hand-driven piles at 1g -which are the closer case to wished in place piles due to the low stress levels during driving.

In this study, the slightly larger apparent lateral capacity measured for the vibro-driven pile relative to the impact-driven pile should be interpreted with caution, as it may partly reflect experimental artefacts associated with the vibro-driver platform and counterweight system resisting lateral motion. Nevertheless, the overall trends clearly indicate that installation method and stress level have a preponderent influence on lateral pile performance, supporting the need for installation-aware modelling approaches in offshore wind foundation design.

5 CONCLUSIONS

This study demonstrates the suitability of geotechnical centrifuge modelling for investigating the influence of installation technique on the lateral behaviour of steel hollow piles. Dedicated miniature instruments, a vibro-driver, an impact hammer, and a lateral loading actuator, were developed and deployed to enable controlled, in-flight installation and subsequent lateral testing under representative stress conditions.

The results indicate that piles installed under centrifuge acceleration exhibit a noticeably stiffer initial lateral response and higher lateral resistance than hand-driven piles at 1g in monotonic loading, while lateral resistance of a hand-driven pile at 1g appears to converge towards the one of an in-flight installed pile during cyclic loading. This confirms that installation stress history, and cyclic lateral loading history strongly influence lateral pile performance. Furthermore, results with hand-driven piles at 1g or wished-in-place piles should be analysed with caution.

While vibro- and impact-driven piles show similar trends in lateral stiffness and capacity in these dry sand tests, the slightly higher apparent capacity of vibro-driven piles should be interpreted with caution due to experimental artefacts associated with the vibro-driver platform, which could not be detached prior to lateral loading. Consequently, further analysis and refined experiments are needed to isolate the effects of installation technique and enable a direct, unbiased comparison between vibratory and impact-driven piles.

Overall, this work provides a methodology and preliminary evidence of the installation-dependent lateral response of piles, forming a foundation for future investigations in more representative soil conditions and for developing installation-aware design approaches for offshore monopile foundations.

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