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Comparison of the lateral response of an in-flight vibratory-driven and a hand-driven at 1-g pile in sand in a geo-centrifuge

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ABSTRACT: The installation method of offshore monopiles can significantly influence their lateral capacity and stiffness, which are critical parameters in foundation design for offshore wind turbines. Vibratory driving has emerged as a promising alternative to traditional impact driving, offering potential reductions in noise emissions and installation time. However, its effect on the lateral response of the driven pile remains insufficiently understood. This work presents the development and first use of a combined in-flight vibratory installation and cyclic lateral loading apparatus within TU Delft's geotechnical centrifuge. The system enables the vibratory installation of model piles at prototype stress levels, followed by monotonic or cyclic lateral loading without sample repositioning. Two initial cyclic tests are reported: one with a pile manually inserted at 1g, and one vibro-driven in-flight. The results provide preliminary insight into the influence of the installation method on the lateral response of the pile: the vibratory driven pile displays a stiffer response as well as more capacity than the wished-in place pile. The apparatus offers a unique platform for future studies, including the planned addition of impact-driven tests and extended cyclic loading tests. This work lays the foundation for more comprehensive investigations into the link between offshore pile installation technique and in-service lateral performance.

KEYWORDS: monopile, vibratory driving, installation method, geo-centrifuge.

1 INTRODUCTION

The lateral response of offshore foundation is a key factor in the overall design and long-term performance of offshore wind turbines (OWTs). Lateral stiffness, damping, and capacity govern the ultimate response under storm loading and serviceability limits under wind and wave loading, influence fatigue life, and determine how foundations interact with the tower and rotor-nacelle assembly. Yet, despite its importance, lateral behavior after installation, particularly following alternative driving methods, remains poorly documented.

One such alternative is vibratory driving, a technique in which vertical oscillations are applied to the pile to facilitate penetration. Offshore applications have demonstrated potential benefits such as reduced underwater noise, faster installation, and elimination of uncontrolled "pile run" events (Bienen, 2025). The method is also scalable by combining multiple vibratory drivers. However, its uptake for large-diameter monopiles has been slow, in part due to uncertainties about post-installation performance, especially under lateral loading.

Traditionally, monopiles, large hollow steel cylinders up to 10 m in diameter and weighing over 2000 t, are installed by impact hammering (WindEurope, 2021). This well-established approach generates high-intensity noise that can disturb marine fauna (Bailey *et al*., 2010), imposes significant stress cycles on the pile, and faces scaling challenges as dimensions increase.

Research on vibratory installation has a long onshore history (Viking, 2002) and has often centered on axial capacity and driveability. More recent offshore-focused studies have begun addressing the influence of installation technique on driveability and subsequent lateral response, both at small or medium scale in the laboratory (Shahrour, 2024; Peccin da Silva, 2023) medium scale in the field (Achmus *et al*., 2020; Tsetas *et al*., 2023; Letizia *et al*., 2024; Maes *et al*., 2025) and in physical modelling facilities such as geotechnical centrifuges (Mazutti *et al*., 2025, Simonin *et al*., 2025).

The GEOLAB-funded FoundEx project, which employed a miniature vibratory driver developed at UCLouvain within TU Delft's geo-centrifuge, has provided new insights into the influence of vibratory driving parameters and advanced the broader understanding of this installation technique. Collaboration between UCLouvain and TU Delft continues with the objective of comparing the lateral response of piles installed in sand under different driving techniques. This research will encompass the use of the vibratory driver, as well as an impact hammer (Quinten *et al., 2022*) and a lateral loading system (Orakci *et al*., 2024) both developed at TU Delft. By combining in-flight installation with subsequent cyclic lateral loading under high-stress conditions, the study aims to clarify how installation method influences lateral behavior

This paper presents the apparatus and reports initial results from comparative tests on an in-flight vibratory-driven pile and a pile statically inserted by hand at 1g in dry sand.

2 APPARATUS

The 9 ton.g beam-type geo-centrifuge at TU Delft (1.22 m radius) was used with a centrifugal acceleration of 50-g.

2.1 *Sand sample*

The dry sand samples were prepared in a 295mm internal diameter and 190mm internal height cylindrical container. Dense dry GEBA sand, which characteristics are presented in Table 1, with a relative density $D_r = 80\%$ was used.

The sand sample height within the container was 160mm, and the application radius of the 50-g centrifugal acceleration was set to one-third of its depth.

Table 1. GEBA SAND material properties (Beroya-Eitner et al. (2022))

Parameter	Symbol	Value	Unit
Median grain size	D_{50}	0.119	mm
Coefficient of uniformity	C_u	1.59	-
Max. void ratio	e_{max}	1.07	-
Min. void ratio	e_{min}	0.64	-
Specific gravity	ρ_s	2.67	-
Critical state friction angle	φ_c	31.7	-

2.2 *Miniature pile*

The characteristics of the stainless-steel pile used in this study are presented in Table 2, along with the corresponding prototype dimensions at 50-g.

Although the prototype dimensions are smaller than those of full-scale monopiles, their embedment-to-diameter ratio and dimensions are comparable to that used in medium-scale field tests (e.g., McAdam *et al.,* 2019, Byrne *et al*., 2025; Achmus *et al*., 2020), which will allow in the future the results of this study to be meaningfully compared with such tests through appropriate scaling.

Table 2. Model and prototype dimensions of the driven pile for N=50

Quantity	Model	Prototype
Pile diameter	25 mm	1.25 m
Pile wall thickness	0.5 mm	25 mm
Pile height	210 mm	10.5 m
Pile weight	60 g	7.5 t
Embedment	75 mm	3.75 m

2.3 *Lateral loading rig*

The actuator (see Orakci *et al*., 2024) is presented in Figure 1.

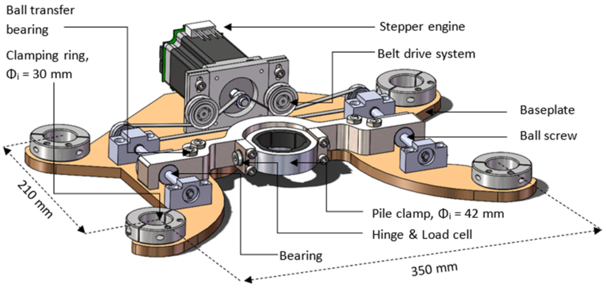

Figure 1. Lateral load actuator.

The lateral loading actuator used in this study was developed at TU Delft to operate under centrifuge accelerations up to 100 g, with a maximum lateral capacity of 5 kN. which scales to 12.5 MN at prototype-scale for a 50-g centrifugal acceleration. It is mounted directly onto the centrifuge carrier and integrates with existing pile installation hardware, enabling lateral loading to be applied immediately after installation without halting the centrifuge. This preserves the in-situ stress state around the pile, improving the realism of the tests.

The actuator consists of a height-adjustable loading frame driven by a stepper motor and belt-ball screw system, with load applied through a central pile clamp fitted with interchangeable ring inserts for piles up to 50 mm in diameter. Rotational bearings minimize bending moments during loading, while a temperature-compensated load cell records applied loads and a laser displacement sensor measures pile head movement independently of actuator deformation. The system can operate in load or displacement control, with cyclic loading frequencies up to 1 Hz and monotonic displacement capacities up to 0.1 pile diameters at the mudline.

2.4 *Miniature vibratory driver*

The miniature vibro-driver used in this study was developed at UCLouvain for use in the TU Delft geo-centrifuge for FoundEx, a GEOLAB project, and is presented in Simonin *et al.* (2024) and Simonin *et al.* (2025). It is designed to replicate the key operating principles of full-scale offshore vibratory hammers. Vertical vibrations are generated by a pair of counter-rotating eccentric masses, driven via a high-speed brushless EC motor and gear system, operating at frequencies up to 1.5 kHz to satisfy centrifuge scaling requirements. The design allows straightforward adjustment of vibration frequency, eccentric moment (2 to 200 g.mm), and static system weight to explore their influence on driveability and foundation performance.

Note that the design of the vibratory driver has been updated: the static and dynamic centers of masses of the driver are more closely aligned with the pile central vertical.

The hammer is mounted on a guided platform with PTFE-lined bushings to ensure vertical alignment during driving and to permit subsequent lateral loading without removal from the soil. This guiding system has been improved for the research presented herein: the two guiding rails and bushings have been moved closer to the center of mass of the system to reduce friction due to misalignment and the risk of jamming. Note that the friction in the previous system was measured at 1-g and already remained below 2 N.

A counterweight and spring system is incorporated to achieve a representative pile-to-hammer weight ratio and to enable parametric variation of static weight effects. The compact frame maintains precise alignment of all moving components while allowing rapid replacement of gears, bearings, or eccentric masses between tests. This flexibility enabled systematic investigation of the governing parameters for vibratory installation of model piles in sand under realistic stress conditions in the centrifuge (Simonin *et al.*, 2024).

The updated driver platform is shown in Figure 2.

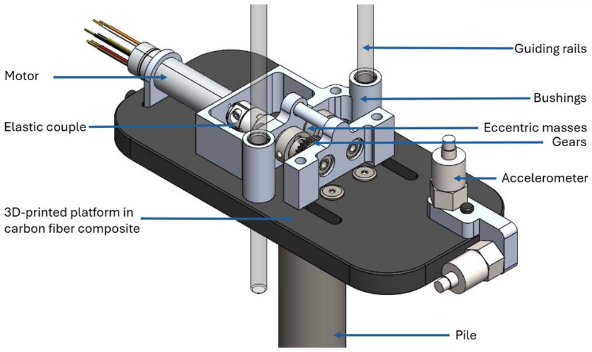

Figure 2. Updated design of the vibratory driver platform.

3 DRIVING AND LATERAL LOADING EXPERIMENT

This section presents two lateral loadings with the same embedment (L/D = 3) of the model pile:

- First experiment: the pile was hand-driven at 1-g, the centrifuge was spun to 50-g, and the lateral loading actuator applied a displacement-controlled cyclic lateral loading to the pile.
- Second experiment: the centrifuge was spun to 50-g, the vibratory driver automatically activated, driving the pile to the desired embedment, and then the lateral loading actuator applied the same cyclic lateral loading.

3.1 *Hand-driving of the pile*

For the hand driving of the pile at 1-g, advantage was taken of the guiding system of the vibratory driver to ensure vertical installation of the pile. Its advancement was measured by a laser sensor, ensuring a precise 75 mm embedment.

3.2 *Vibratory driving of the pile*

The vibratory driver parameters were set to an eccentric moment of 4 g.mm, and a vibration frequency of 1 kHz. These are the standard parameters used in Simonin et al. (2025), and at prototype scale they represent a 25 kg.m eccentric moment for a 20 Hz vibration frequency (a representative frequency for offshore vibratory drivers).

The vibratory driver automatically started after a 30 s waiting period once 50-g centrifugal acceleration was reached, and it was stopped when the pile embedment depth reached 75 mm thanks to a feedback loop with an additional laser sensor. However, the driving was slower here (112 s) than in Simonin et al. (2025) (~30 s), as shown in Figure 3. This difference could be due to the update of the vibratory driver, but it is more likely due to friction between the pile and the lateral loading ring insert connecting it to the lateral actuator. This will be corrected in future studies.

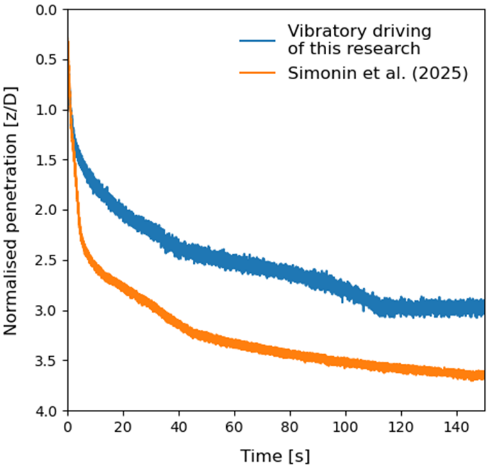

Figure 3. Vibratory driving curve.

3.3 *Comparison of monotonic lateral response*

Figure 4 presents the lateral load applied by the lateral actuator against the lateral displacement measured just above the mudline by a laser sensor. The loading rate was 0.2 mm/s at both model and prototype scales.

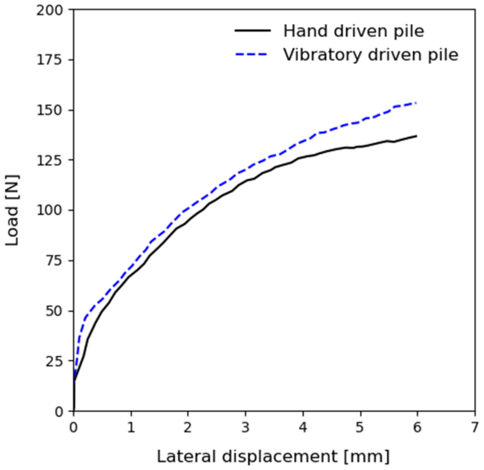

Figure 4. Monotonic response of the model near the mudline.

The loading is applied via the 20 mm thick ring insert that can freely rotate around the horizontal axis perpendicular to the loading direction. Assuming that the load is transmitted on average at half the height of the loading ring, the loading eccentricity for the tests is h = 60 mm, which gives an eccentricity ratio of h/D = 2.4.

Figure 4 shows that the in-flight vibratory driven pile presents a moderately stiffer and stronger response than the hand driven pile at 1-g.

Scaling of the lateral response to the prototype scale is done by multiplying the displacement by 50, and the force by 50^2. The up-scaled responses are pictured in Figure 6.

This result cannot be directly compared to prototype scale experiments, as the diameter of the pile and eccentricity do not match (McAdam et al., 2019; Achmus et al., 2020), as well as the embedment ratio (Achmus *et al.*, 2020).

Numerical results by Orakci *et al.* (2024) cannot be directly compared either as the embedment ratio considered in this study was L/D = 5 rather than 3 here. However, the capacity at 0.1D displacement at the mudline with advanced constitutive models of 400 kN and 500 kN (Orakci et al., 2024) is coherent with the results presented herein.

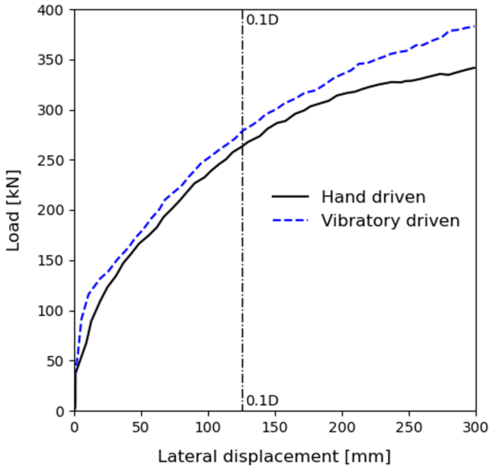

Figure 5. Monotonic response near the mudline scaled to prototype dimensions.

3.4 *Comparison of cyclic lateral response*

Figure 6 presents the cyclic lateral loading results, where the two two-way cycles were displacement controlled based on the displacement at the loading frame level.

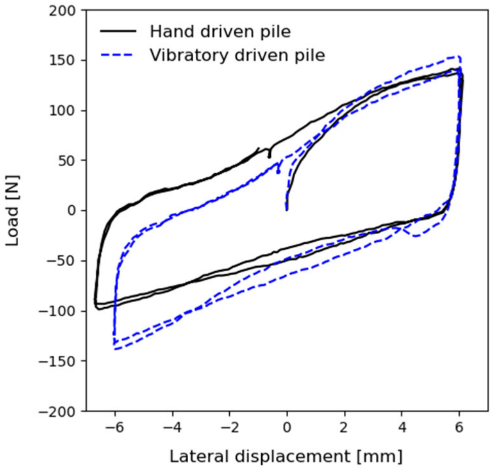

Figure 6. Cyclic response of the model near the mudline.

The secant stiffness appears larger for the vibratory driven pile than for the hand driven pile, while the hysteresis loops appear to approximately amount to the same.

4 CONCLUSION AND PERSPECTIVES

This preliminary centrifuge study compared the lateral response of model piles installed in dense dry sand by manual insertion at 1-g and by in-flight vibratory driving at 50-g. The vibratory-driven pile showed moderately higher stiffness and capacity under monotonic and cyclic loading, while hysteretic energy dissipation remained similar.

These results highlight the influence of installation techniques on lateral performance, even at small scale and low embedment ratios, and demonstrate the capability of applying lateral loading immediately after in-flight installation. The methodology establishes a foundation for future systematic comparisons of vibratory and impact driving, enabling improved prediction of monopile behavior and supporting more efficient, environmentally responsible offshore wind foundation design.

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6 REFERENCES

Achmus, M., Schmoor, K.A., Herwig, V., Matlock, B. (2020). Lateral bearing behaviour of vibro- and impact-driven large-diameter piles in dense sand. *Geotechnik*, 43-3, pp. 147-159.

Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G. and Thompson, P.M. (2010). Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. Marine Pollution Bulletin, 60(6), pp. 888-897, ISSN 0025-326X. DOI: 10.1016/j.marpolbul.2010.01.003

Beroya-Eitner, M. A., Machaček, J., Viggiani, G., Dastider, A. G., Thorel, L., Korre, E., Agalianos, A., Jafarian, Y., Zwanenburg, C., Lenart, S., Wang, H., Zachert, H., & Stanier, S. (2022). GEOLAB Material Properties Database (1.0) [Data set]. Zenodo. DOI: 10.5281/zenodo.7462287

Bienen, B. (2025). Geotechnical Engineering for Large Infrastructure Projects Such as Offshore Wind Farms. In: Indraratna, B., Rujikiatkamjorn, C. (eds) Recent Advances and Innovative Developments in Transportation Geotechnics. Springer, Singapore. DOI: 10.1007/978-981-97-8245-1_18

Byrne, B.W, Buckley, R.M., Burd, H.J., Crispin, J., Houlsby, G.T., Kamas, I., Keane, R., Malhotra, S., Martin, S., Nardelli, V., Qiu, Z. H., Rasmussen, M., Shonberg, A., Simonin, L.E.J., Soares Cunha, V., Vaitkune, E., Wen, K.Z., Wu, K.W. (2025). PICASO: Cyclic loading of wind turbine monopiles. In: *Proceedings of the ISFOG2025*, Nantes, France, 9-13 June 2025. ISSMGE website, DOI: 10.53243/ISFOG2025-506

Letizia, N., Anoyatis, G., Simonin, L., Rattez, H., Collin, F., Francois, S., Claes, H., Soete, J. (2024). Geotechnical characterization of a test site in Zeebrugge for large scale tests of monopiles in the framework of the SAGE-SAND project. In: *Proceedings of the XVIII ECSMGE 2024*, 26-30th August 2024, Libson, Portugal.

Maes, K., Simonin, L.E.J, Bayart, C., Bertholet, A., Anoyatis, G., Rattez, H., Francois, S. (2025). Experimental Investigation of the Installation and Lateral Capacity of Instrumented Monopiles at the SAGE-SAND Test Site in Zeebrugge. In: *Proceedings of the ISFOG2025*, Nantes, France, 9-13 June 2025. ISSMGE website, DOI: 10.53243/ISFOG2025-432

Mazutti, J., H., Bienen, B., Bransby, M., F., Randolph, M., F. and Wager, G. (2025). Development of a mini vibro-driver for pile testing in the centrifuge. *International Journal of Physical Modelling in Geotechnics*, 25-1, pp. 34-48. DOI: 10.1680/jphmg.23.00056
https://doi.org/10.1680/jphmg.23.00056

McAdam, R.A., Byrne, B.W., Houlsby, G.T., Beuckelaers, W.J.A.P., Burd, H.J., Gavin, K.G., Igoe, D.J.P., Jardine, R.J., Martin, C.M., Muir Wood, A., Potts, D.M., Skov Gretlund, J., Taborda, D.M.G., Zdravković, L. (2019). Monotonic laterally loaded pile testing in a dense marine sand at Dunkirk. *Géotechnique*, 70-11, pp. 986-998.

Orakci, O., Simonin, L.E.J., Quinten, T., Cabrera, M.A., Francois, S., Anoyatis, G., Chow, S.H., Tian, Y., Rattez, H. (2024). Monopile under lateral loading: centrifuge testing and numerical investigation. In: *Proceedings of the 5th ECPMG 2024*. 2-4th October 2024, Delft, Netherlands. DOI: 10.53243/ECPMG2024-119

Peccin Da Silva, A., Post, M., Elkadi, A., Kementzetzidis, E., and Pisanò, F. (2023). Effect of installation parameters and initial soil density on the lateral response of vibratory-driven monopiles: a laboratory study. In: *9th Offshore Site Investigation and Geotechnics (OSIG 2023) Conference*. 12th-14th September 2023 in London, United Kingdom.

Quinten, Q., Askarinejad, A., Gavin, K., Van Beek, C. (2022). Development of an impact pile driving system for the geotechnical centrifuge at Delft University of Technology. In: Proceedings of ICPMG2022, 19-23 September, Seoul, Korea.

Shahrour, M. (2024). Influence of vibratory pile driving on offshore wind turbine mechanical behaviour. Master thesis, UCLouvain.

Simonin, L.E.J., Rattez, H., Herman, B, Ovalle-Villamil, W., Quinten, T., Cabrera, M.A., Wehbe, T., Orakci, O., Anoyatis, G., Francois, S. (2024) Investigation of vibro-driven monopiles in a geo-centrifuge. In: Proceedings of the 5th ECPMG 2024. 2-4th October 2024, Delft, Netherlands. DOI: 10.53243/ECPMG2024-111

Simonin, L.E.J., Rattez, H., Ovalle Villamil, W.F., Cabrera, M.A., Anoyatis, G., Francois, S. (2025). Influence of vibro-driver frequency on pile penetration in dry sand in a geotechnical centrifuge. In: *Proceedings of the ISFOG2025*, Nantes, France, 9-13 June 2025. ISSMGE website, DOI: 10.53243/ISFOG2025-367

Tsetas, A., Tsouvalas, A., Gómez, S.S., Pisanò, F., Kementzetzidis, E., Molenkamp, T., Elkadi, A.S.K., Metrikine, A.V.(2023). Gentle Driving of Piles (GDP) at a sandy site combining axial and torsional vibrations: Part I - installation tests, *Ocean Engineering*, 270. DOI: 10.1016/j.oceaneng.2022.113453

Viking, K. (2002). *Vibro-driveability - a field study of vibratory driven sheet piles in non-cohesive soils*. Doctoral thesis, Royal Institute of Technology, Stockholm, Sweden.

Wind Europe (2021) Offshore wind in Europe—key trends and statistics 2020. Available at: [https://windeurope.org/intelligence-platform/product/offshore-wind-in-europe-key-trends-and-statistics-2020/] accessed 30/10/2024.