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Centrifuge modelling of anchor piles under multi-directional loading for floating wind turbines

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ABSTRACT: The current frontier for the offshore wind industry lies in achieving economic and technical viability for floating structures, facilitating the development of deeper wind farms previously inaccessible with bottom-fixed structures. This paper presents an innovative experimental centrifuge set-up developed as part of the MUTANC project to investigate the behaviour of shared anchors to multi-directional horizontal loads, mimicking the effects of multiple catenary mooring lines acting simultaneously on a typical anchor pile. A steel model pile equipped with fibre optic sensing allows for the recording of normal strains along the pile shaft and bending moment, enabling the derivation of soil reaction and pile deflection. The paper also investigates the potential decoupling of loading in perpendicular directions and outlines preferred responses to various monotonic multidirectional load paths. The results validate the setup's reliability, serving as a benchmark for subsequent cyclic tests to generate an innovative database for the validation of numerical models.

1 INTRODUCTION

The offshore wind industry has shown a steady trend toward installing larger turbines in deeper offshore waters, where wind resources are greater and more consistent. Traditional fixed-bottom structures, such as monopiles, are limited to depths of 60m with current design standards, necessitating the development of floating solutions for deeper areas.

Commercialisation of floating wind farms requires important cost reduction in the mooring system, for which geotechnical engineering advancements play an important role. One promising solution considers employing shared anchors to moor several floating wind turbines. However, this requires anchor foundations to withstand multi-directional loading, which has not been thoroughly investigated yet. This is to avoid the risk of cascading failure in a large farm of over 100 turbines all linked to each other through mooring. Fontana et al. (2018) performed a study on a multiline anchor concept for a Floating Offshore Wind Turbine (FOWT) plant demonstrating how the number of anchors would significantly reduce. On the other hand, lines and foundations must be able to resist any load direction.

The magnitude and inclination of environmental loads acting on an anchor depend on the mooring type. At present, catenary moorings are one of the most commonly used for offshore installations (Cerfontaine et al., 2023), generating pure horizontal loads on the anchor at the mudline.

Richards (2019) explored the effect of multi-directional loading on a rigid monopile through successive campaigns of tests at 1*g*, some of which were scaled in the centrifuge. The study demonstrates that the hysteretic response of the foundation under multidirectional tests closely mirrors that induced by cyclic unidirectional loading, but with increased energy dissipation. However, the monopile dimensions are not representative of intermediate, more flexible, anchor piles. Numerical modelling studies by Su & Li (2013), Lovera et al. (2021), and Jenck et al. (2021) explored the effects of multidirectional loading on lateral resistance and displacement, revealing lower lateral resistance under multidirectional loading and highlighting the need for considering load direction changes in design.

This paper presents the first experimental campaign of the MUTANC project, which aims to investigate the technical and economic feasibility of using shared anchor piles to reduce the cost of floating wind. As part of this project, a geotechnical centrifuge test campaign is planned to further understand the behaviour of shared anchor piles under strong multi-directional cyclic loading, as well as the implications for design and potential increases in geometry. This paper shows the bespoke experimental set-up developed for this project, together with the first results which enable validation of the experimental procedure, in particular the sample preparation. The results also permit to drawing of preliminary observations on the performance of anchor piles to monotonic horizontal multi-directional loads.

2 EXPERIMENTAL SETUP

The tests presented in this paper were performed at the Gustave Eiffel University (UGE) geotechnical centrifuge facility in Nantes, France. The machine is equipped with a 5.5 m radius beam and can perform experiments with a gravity acceleration 100 times greater than the Earth's (N = 100). The tests of the presented campaign are performed at an acceleration level of N = 83.3.

2.1 Load actuators

Two actuators, one electric and one hydraulic, exert loads on the pile by pulling its head using rope cables, located at 0.5D above the mudline, horizontally and quasi-near the soil surface (Figure 1). These actuators are positioned above the pile on a steel beam frame built into a sturdy sand-filled strongbox (Figure 1, Figure 2, Figure 3a). The electric actuator is constituted of a linear roller screw motor with a stroke length of 300 mm and a minimum resolution of 30 µm. The actuator can withstand forces up to 8.365 kN. The hydraulic actuator is equipped with a stroke length of 350 mm and a force of up to 35 kN. A displacement transducer with a resolution of up to 1 µm is used to control the range of the hydraulic actuator. Both actuators were manually controlled in force and operated to a designated maximum value of the pulling force on the pile.

2.2 Instrumentation

The model pile (Figure 3, Table 1) is made of C45 steel (Table 2), selected for its large minimum yield tensile strength and for its considerably large ultimate tensile strength. This guarantees sufficient strength with no bending damage of the pile under lateral

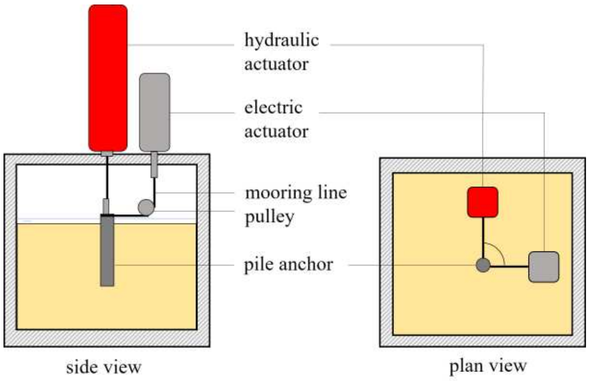

Figure 1. Setup used for the presented campaign.

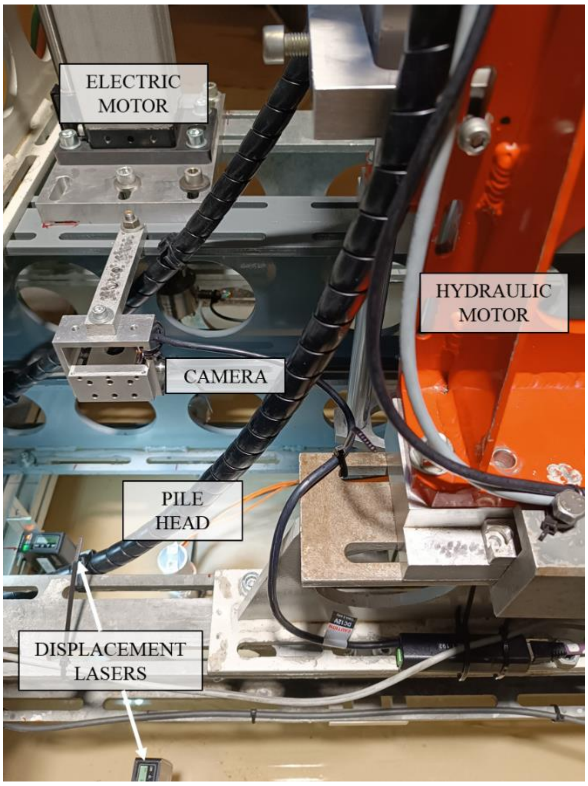

Figure 2. Overview of the experimental setup installed in the centrifuge basket.

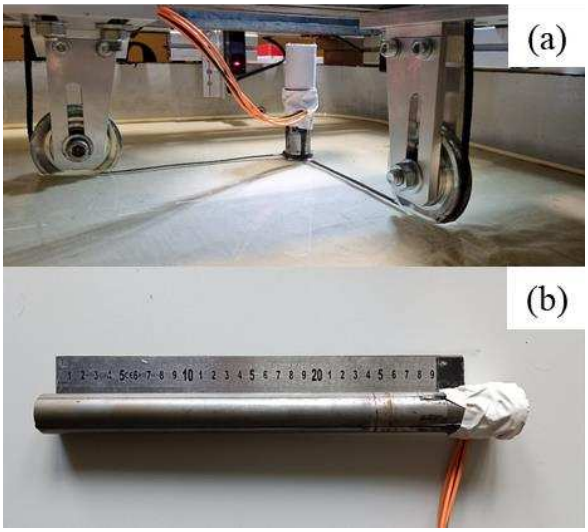

Figure 3. (a) Model pile installed in the sand sample and connected to the actuators. (b) Instrumented pile.

Table 1. Geometry of the foundation.

Symbol	Model (mm)	Prototype (m)
D (pile diameter)	30	2.5
t (pile thickness)	1.25	0.104
L (pile length)	240	20

Table 2: Mechanical properties of C45 steel.

Property	C45
σ_e (MPa)	305-335
σ_m (MPa)	590-770
ε_m (%)	6-16
E (GPa)	190

Table 3. Properties of the Fontainebleau NE34 sand.

Property	Value
C_u	1.53
d_{50} (μm)	210
$\rho_{d,min}$ (g/cm^3)	1.46
$\rho_{d,max}$(g/cm^3)	1.71
e_{max}	0.549
e_{min}	0.753

loading while enabling the use of fibre optic (FO) sensing along the shaft of the pile.

Technical fibre rope cables are used to transfer forces from the load actuators by pulling the pile. The diameter of the rope cable is 5 mm. With a breaking strength of 26 kN at a strain of 2.8%, this cable can sustain a maximum tensile stress of 1.32 GPa.

The model pile is equipped with optic fibres along its shaft at four positions. Each optic fibre has ten Fibre Bragg Grating (FBG) sensors distributed every 20 mm. FBGs operate on the principle of light reflection. When a light beam encounters an FBG, it undergoes partial reflection, causing light to accumulate and form a peak when an integer multiple of the light wavelength fits within twice the fringe spacing. External stress or temperature changes cause the optical fibre to contract or expand, altering the fringe spacing and consequently shifting the reflected peak wavelength in the recorded spectra. This shift allows for the calculation of the fibre's strain. This equipment was used successfully for instrumenting monopiles for centrifuge modelling (Li et al., 2020) and provides valuable data on pile deflection, bending moment and soil reaction.

A distance sensor (OM70) and a circle measurement sensor (OXC-7) were fixed to the setup frame so that the position of the pile head would continuously be tracked. The OM70 laser sensor can measure objects that are between 100 (linear error 30μm) and 150mm (linear error 90 μm) from the laser emitter. The OXC-7 can detect the position of rounded objects with a diameter from 30 to 130mm positioned at distances between 150 (linear error 35μm) and 250mm (linear error 60μm) from the laser emitter.

Ground-level displacement, pile rotation, strain, and applied load are inferred through the processing of data from the distance lasers and from the optical fibres placed along the pile shaft. The approach is described by Li et al. (2020) and further illustrated by Blanc (2024).

2.3 Sample preparation

The sand sample is prepared using a sand-raining technique that permits to control the relative density through sand pluviation and provides samples that are homogeneous in controlled and repeatable conditions (Garnier, 2001). The model soil is a poorly graded NE34 Fontainebleau sand (Table 3). For laterally loaded slender piles, it was established how scale effects fade in significance for models with D/d_{50} > 60 (Garnier et al., 2007). In the present campaign, this condition is respected (D/d_{50} > 140).

The sand was dropped from a constant height and deposited into a 1200 mm (length) by 800 mm (width) by 360 mm (height) rectangular strongbox. The sample was prepared by raining the sand from a 70 cm height with an automatic hopper moving back and forth over the strongbox, achieving a relative density for this test of about 80%.

To simulate the prototype condition where the foundation is underwater, the sand was saturated by slowly injecting water through four draining channels located at the bottom of the strongbox. The attained water table was about 20 mm above the sand surface. The fluid used in this test was water (as opposed to methylcellulose) because the loading conditions were perfectly drained, hence not requiring scaling of the pore fluid. Saturation enabled to achieve appropriate effective unit weight and aided pile installation.

2.4 Test programme and load history

The presented experimental campaign aims to validate the test set-up presented above and to collect preliminary information about the response of piles loaded in multiple directions.

As part of the set-up validation, attention was provided to the sample preparation to ensure that homogeneity was not going to pollute results on multi-directional loading: as the sand raining process occurs along a preferential direction, this might affect the response of the model foundation when loaded in multiple directions. Previous works at the centrifuge facility of UGE had confirmed that this preparation procedure would lead to a satisfactory homogeneity

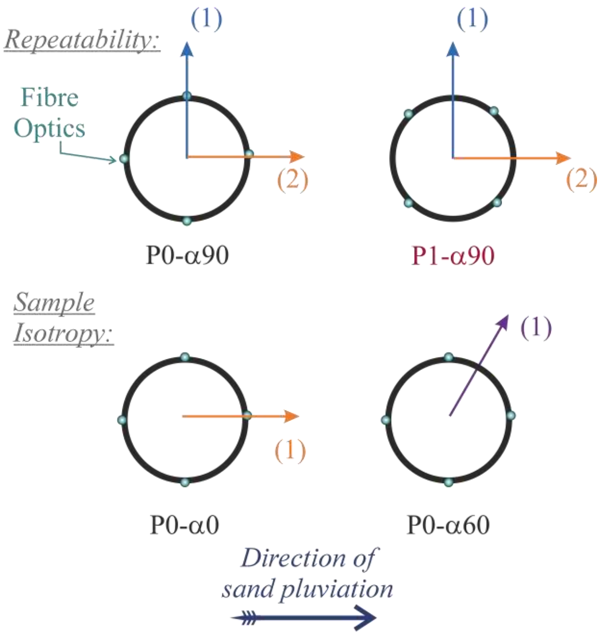

Figure 4. Schematic of test campaign.

Table 4. Test programme.

ID	Angle of loading*	Angle of FO**	Loading history
P0-α90	90°	0°	(1) Exceeds H_{R1} (2) Exceeds H_{R2}
P1-α90	90°	45°	(1) Exceeds H_{R1} (2) Exceeds H_{R2}
P0-α0	0°	0°	(1) Exceeds H_{R1}
P0-α60	60°	0°	(1) Exceeds H_{R1}

* Angle of first principal loading compared with sand pluviation direction – enables to assess effects of sample anisotropy (Figure 4).

** FO = Fibre Optic. Angle of the fibre optics compared with loading direction (1) (see Figure 4).

and isotropicity of sand samples (Ternet, 1999) but this work was repeated here.

Four tests were performed to explore the influence of pile orientation, sequence and level of load on the response of the foundation. Tests were conducted with a load-controlled approach to a reference horizontal load at pile head H_R (~12.5 MN). This limit corresponds to a pile displacement threshold of 0.1D, inducing large plastic deformation in the soil. This value was established during a preliminary test where the pile was pushed monotonically to its ultimate capacity. The adopted loading paths for this campaign can be visualised Figure 4, with details of the loading levels for each test given in Table 4.

3 RESULTS

3.1 Global pile response

The results from the pile tests are compared in terms of load-displacement curves (Figure 5), with colours of load directions matching the colour code of Figure 4.

Comparing tests P0-α90 and P1-α90 demonstrates the repeatability of the testing procedures for both the first (1) and for the second (2) loading direction (Figure 5a). Tests P0-α0 and P0-α60 are compared to test P0-α90 to confirm the isotropicity of the soil

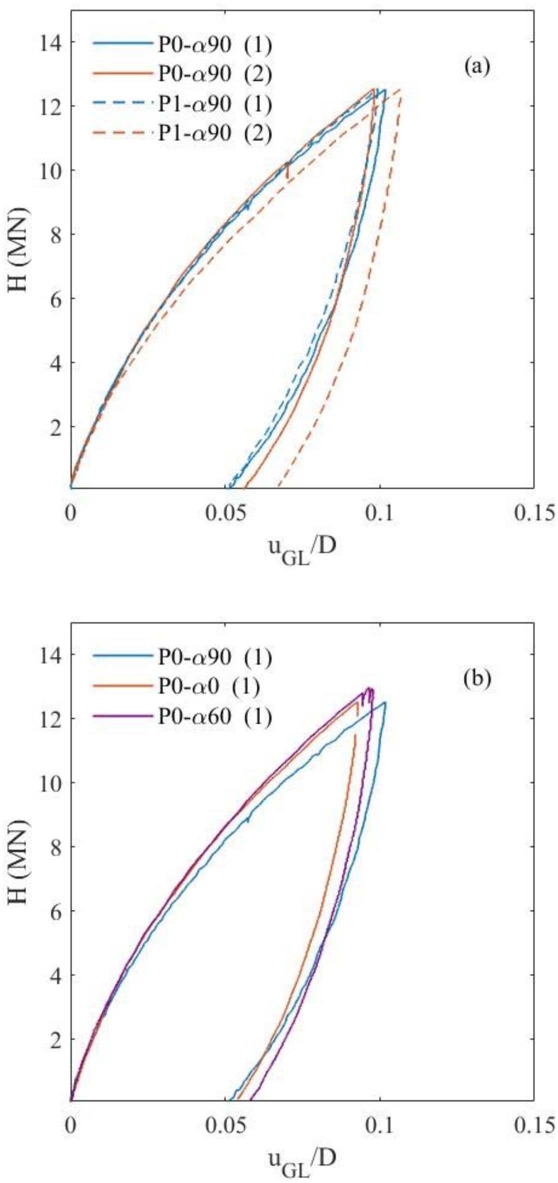

Figure 5. Load-displacement curves from different tests are compared to confirm the quality of the experimental set-up. (a) Repeatability of the tests. (b) Isotropicity of the soil sample.

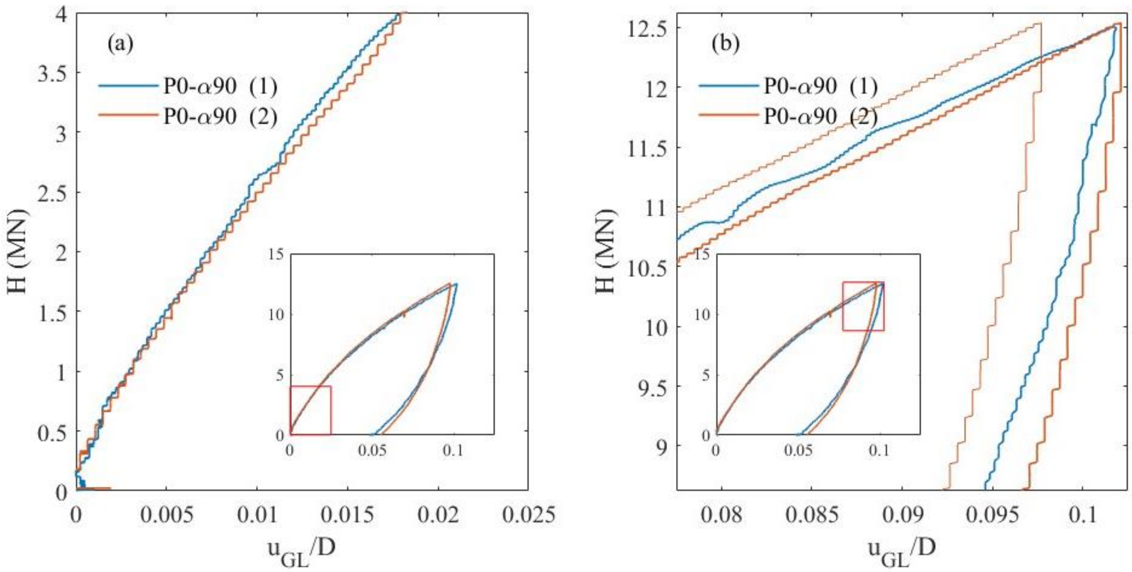

Figure 6. Details of the behaviour of the tested anchor pile on multiple directions. (a) Small displacement stiffness. (b) Unloading stiffness to H_R: loading direction (2) was moved to match the peak of loading (1) for better direct comparison of the unloading stiffness. The original curve is reported in light orange.

sample. The results shown in Figure 5b prove that there is no dependence on the response of the sand to the direction of loading, demonstrating that the sample preparation technique does not induce any preferential load path and that the obtained sample has isotropic properties. This observation validates the sample preparation procedure employed in the laboratory.

Figure 5a also shows the response of the anchor to a multidirectional loading path, with two successive, 90° distant monotonic loads increasing to the load reference value H_R . Re-loading along a direction (2) occurs after an original loading-unloading path along (1). Both P0-α90 and P1-α90 tests show no coupling between the two directions.

Figure 6a illustrates the small-strain stiffness of the pile by zooming on the initial portion of the load-displacement curve. The plot shows that the pile stiffness is comparable when loading along successive directions (1) and (2), meaning that the load (2) is unaffected by the load (1) when their distance is a 90° angle. This observation is also valid for the unloading stiffness (Figure 6b). The residual displacement after unloading seems unaffected by multi-directional loading in this instance, and conforms to general observation from single-directional monotonic loading of piles in sands (e.g. Abadie, 2015; Abadie et al., 2019).

3.2 Pile bending

Measurements from the optical fibres are used for tracking deformations of the pile shaft along the test

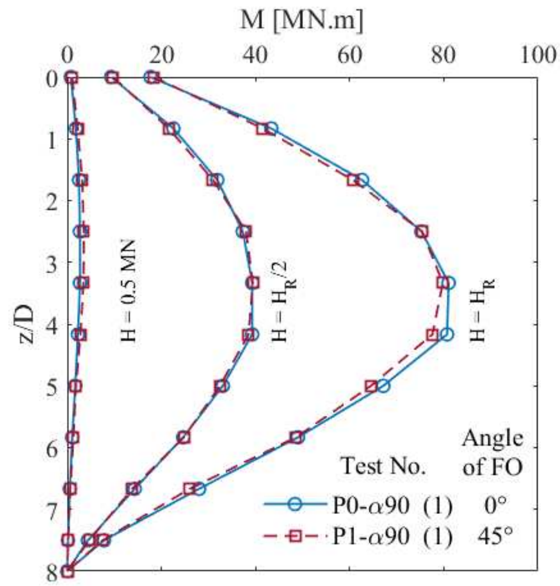

Figure 7. Profiles of bending moment at progressive levels of horizontal load (H = 0.5 MN, $H = H_R/2$, $H = H_R$) comparing two different tests, P0-α90 and P1-α90. when loaded perpendicularly to the sand raining.

and can be used to infer bending moment profiles at progressive levels of load, with examples of results provided in Figure 7. This is typically used to validate the structural integrity of the design of the pile and to derive soil reaction curves. In this paper, the results are used to verify the instrumentation techniques of the pile using fibre optic sensing. The results indeed show good independence of the fibre optic sensing measurement to the angle of loading, with further information on techniques for strain and bending moment measurement derived from fibre optic sensing for laterally loaded piles in centrifuge experiments provided in Blanc (2024).

4 CONCLUSIONS

This paper presents the experimental set-up for the centrifuge modelling of the MUTANC project. This aims to investigate the behaviour of shared anchor piles embedded in sand subjected to multidirectional horizontal loads. A model pile equipped with four optical fibres installed along the shaft is tested in a centrifuge facility. Displacement sensors are strategically deployed to provide continuous monitoring of the model's response throughout the experiments.

A series of tests were performed to validate the test setup. In particular, the results verified the possibility of sample anisotropy and the influence of loading direction on readings of fibre optic sensing. The tests also enabled to verify the repeatability of the experimental procedure.

Comparing load-displacement curves of tests P0-α0 and P0-α60 with P0-α90 confirms the isotropicity of the sample and validates the sample preparation procedure as well as pile driving methods. Further analysis of the results shows that both strength and small displacement stiffness of the foundations are uncoupled to loading directions (i.e. first and second loading responses of test P0-α90 are very similar).

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REFERENCES

Abadie, C. (2015). Cyclic lateral loading of monopile foundations in cohesionless soils (PhD thesis). University of Oxford.

Abadie, C. N., Byrne, B. W., & Houlsby, G. T. (2019). Rigid pile response to cyclic lateral loading: laboratory tests. Géotechnique, 69(10), 863-876. https://doi.org/10.1680/jgeot.18.p.277

Blanc, M. (2024). Progress in instrumentation techniques for model piles in geotechnical centrifuge experiments. *5th European Conference on Physical Modelling in Geotechnics*.

Cerfontaine, B., White, D., Kwa, K., Gourvenec, S., Knappett, J., & Brown, M. (2023). Anchor geotechnics for floating offshore wind: Current technologies and future innovations. *Ocean Engineering*, *279*. https://doi.org/10.1016/j.oceaneng.2023.114327

Fontana, C. M., Hallowell, S. T., Arwade, S. R., DeGroot, D. J., Landon, M. E., Aubeny, C. P., Diaz, B., Myers, A. T., & Ozmutlu, S. (2018). Multiline anchor force dynamics in floating offshore wind turbines. *Wind Energy*, *21*(11), 1177–1190. https://doi.org/10.1002/we.2222

Garnier, J., Gaudin, C., Springman, S. M., Culligan, P. J., Goodings, D., Konig, D., Kutter, B., Phillips, R., Randolph, M. F., & Thorel, L. (2007). Catalogue of scaling laws and similitude questions in geotechnical centrifuge modelling. *International Journal of Physical Modelling in Geotechnics*, *7*(3), 01–23. https://doi.org/10.1680/ijpmg.2007.070301

Jenck, O., Obaei, A., Emeriault, F., & Dano, C. (2021). Effect of horizontal multidirectional cyclic loading on piles in sand: A numerical analysis. *Journal of Marine Science and Engineering*, *9*(2), 1–22. https://doi.org/10.3390/jmse9020235

Li, Z.-S., Blanc, M., & Thorel, L. (2020). Using FBGS to estimate the horizontal response of a monopile in a geotechnical centrifuge. *International Journal of Physical Modelling in Geotechnics*, *20*(3), 164–174. https://doi.org/10.1680/jphmg.19.00022

Lovera, A., Ghabezloo, S., Sulem, J., Randolph, M. F., Kham, M., & Palix, E. (2021). Pile response to multi-directional lateral loading using P–y curves approach. *Geotechnique*, *71*(4), 288–298. https://doi.org/10.1680/jgeot.18.P.297

Richards, I. A. (2019). *Monopile foundations under complex cyclic lateral loading [PhD thesis]*. University of Oxford.

Su, D., & Li, J. H. (2013). Three-dimensional finite element study of a single pile response to multidirectional lateral loadings incorporating the simplified state-dependent dilatancy model. *Computers and Geotechnics*, *50*, 129–142. https://doi.org/10.1016/j.compgeo.2013.01.007

Ternet, O. (1999). *Reconstitution et caractérisation des massifs de sable. Applications aux essais en centrifugeuse et en chambre de calibration*. Université de Caen.