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# Cyclic loading of monopiles at a saturated dense sand site in Germany

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**ABSTRACT:** Model testing of medium scale monopile foundations in the field provides the best evidence of full-scale pile behaviour, and hence the basis for the development and validation of new design methods. The PICASO project focuses on the development of new design methods that address cyclic loading of the monopile foundations and explores the accumulated rotation that develops after a number of cycles, as well as the post-cyclic monotonic capacity of the pile. The field test results are interpreted within a hardening plasticity theory that is set within the framework of hyperplasticity, called the hyperplastic accelerated ratcheting model, HARM. The fieldwork includes medium scale pile testing at a stiff clay site in Cowden, UK, completed during 2021, and a dense sand at Cuxhaven in Germany, completed during 2024. This paper describes the details of the field testing at the Cuxhaven dense sand site, and provides: (i) an overview of the site characterisation and the detailed site preparation undertaken for the field testing, (ii) information about the pile designs (1.22 m and 2.50 m diameter) and range of instrumentation adopted, (iii) a description of the loading paths applied to the piles, and the logic behind various of the tests undertaken, (iv) some preliminary cyclic loading data that demonstrates some of the key outcomes from the testing campaign.

**Keywords:** pile testing, cyclic loading, monopiles, sand

## 1 INTRODUCTION

The recent global renewable energy targets are leading to a rapid development of the offshore wind industry and an increase in the capacity of future turbines. Monopiles are the most common type of foundation used to support these structures, with diameters, D, expecting to increase with larger turbines, moving from the typical 8-10 m used currently to 12-15 m (Byrne, 2020). Considering that typical embedded pile lengths, L, are 30-40 m, the embedment ratios, L/D, will likely reduce to between 2 and 3.

New design methodologies for monopiles were developed through the Pile Soil Analysis (PISA) project, during which two testing campaigns developed at Cowden (UK) and Dunkirk (France) were conducted. These focussed on the monotonic behaviour of monopiles but with some testing on cyclic loading. Pile geometries and loading conditions (lateral loading dominant over axial) appropriate to offshore wind problems were selected considering that previous design methods were based on experimental evidence developed for other offshore applications. A

total of 28 tests were performed on piles having diameters of 0.273 m, 0.762 m and 2.0 m (Byrne et al, 2020; McAdam et al., 2020).

The Pile Cyclic Analysis: Oxford and Ørsted (PICASO) project has been developed for updating the design methodologies based on the PISA project results, with a focus on cyclic loading. As for PISA, two sites were specifically selected to study the lateral behaviour of monopiles; a glacial till clay site (Cowden, UK, Martin et al, 2023) and a sand site (Cuxhaven, Germany). These sites provide a close approximation to typical geological conditions encountered in the North Sea. The present article explores the testing campaign performed at the sand site in Cuxhaven, during which 9 medium and 3 large diameter tubular steel piles were laterally tested. L/D ratios of 3 and load eccentricities of 4D, representative of environmental loading, were kept constant for all the tests. A series of "calibration" tests, consisting of monotonic, multi-rate monotonic and sinusoidal cyclic tests, were carried out prior to performing a series of "validation" tests, consisting of uni- and multi-directional random cyclic tests.

The PICASO project consists of 5 work packages (WPs) and the research work included in the present article is part of WP4 (medium-scale field testing). PICASO aims to developing a new design method for lateral cyclic loading of monopiles. The field results are interpreted using a new model set within the framework of hyperplasticity developed by Houlsby and Puzrin (2006), the hyperplastic accelerated ratcheting model (HARM). This model can be developed for any combination of rate effects, ratcheting, and hardening/softening to capture the different characteristics of cyclic loading, combining the benefits of explicit and implicit methods.

## 2 SITE CHARACTERISATION

The PICASO sand site in Cuxhaven was selected for carrying out pile testing at a medium dense to dense silica sand site having characteristics comparable to those encountered in the North Sea. The site is located 16 km south of the town of Cuxhaven (Germany) and 8 km east of the coastline. Most of the area lies on Pleistocene North Sea clean sands, which are deltaic sediments deposited in the German Bight during inter-glacial periods (Knudsen et al., 2019).

The stratigraphy and the sand properties were inferred from 6 boreholes (BHs), 27 cone penetrometer tests (CPTs, including one at each test pile location) and 4 seismic cone penetrometer tests (SCPTs) up to the maximum depth of approximately 20 m below the initial ground level. The initial ground surface was excavated to ensure that all the tests were performed in fully-saturated sand. A piling mat was applied on the top of the newly excavated ground level to provide sufficient resistance for the operations of heavy machinery on site.

The CPT results show that the values of cone resistance recorded are relatively consistent across the whole site, considering the overall maximum and minimum cone resistances along with the mean values, within the range of 2-22 MPa above the large diameter pile toes (Fig. 1a). The results of the SCPTs in terms of maximum shear modulus $G_{max}$ along with an interpretation of the data carried out by means of the expression proposed by Hardin (1978) are shown in Figure 1b. Both results in Figure 1 are presented for reduced levels (RL) relative to the NHN datum, which is used in Germany.

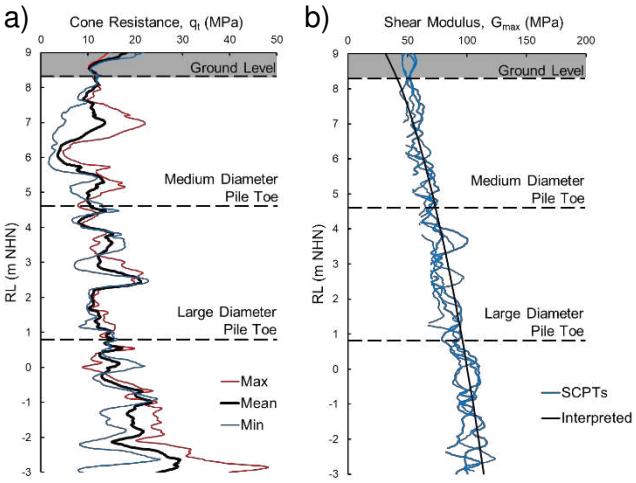


*Figure 1. Profiles of the CPT cone resistance (a) and shear modulus $G_{max}$ (b) with depth.*

## 3 PILE TESTING SPECIFICATIONS

### 3.1 Pile details and instrumentation

The pile testing campaign was carried out on a total of 12 open-ended tubular steel piles, which were installed between October and December 2023 and tested between March and October 2024. 13 reaction piles were installed along with the test piles. The test piles consisted of 9 medium diameter piles (D=1.22 m) and 3 large diameter piles (D=2.5 m). The pile sizes were appropriately chosen considering transportation and installation constraints and were different from those selected for PISA to increase the set of data to facilitate development of scaling relationships. The pile details, including embedded pile length (L), thickness (t) and height of the load application point above the ground level (h) along with the test type performed are reported in Table 1. The test piles were the same used

for the PICASO clay site and additional information on their geometry was reported by Martin et al. (2023). The layout schematic of the site is shown in Figure 2, reporting locations of the test and reaction piles along with part of the boreholes performed.

*Table 1. Pile details and test summary*

| Pile | D (m) | L (m) | t (mm) | h (m) | Test Type |
|---|---|---|---|---|---|
| **P01** | 1.22 | 3.66 | 16 | 4.88 | Multi-rate monotonic |
| **P02** | 1.22 | 3.66 | 13 | 4.88 | Monotonic |
| **P03** | 1.22 | 3.66 | 13 | 4.88 | 1.5-way uni-directional cyclic |
| **P04** | 1.22 | 3.66 | 13 | 4.88 | 1-way uni-directional cyclic |
| **P05** | 1.22 | 3.66 | 13 | 4.88 | 2-way uni-directional random cyclic |
| **P06** | 1.22 | 3.66 | 13 | 4.88 | 2-way uni-directional cyclic |
| **P07** | 1.22 | 3.66 | 13 | 4.88 | 2-way multi-directional random cyclic |
| **P08** | 1.22 | 3.66 | 13 | 4.88 | Multi-way uni-directional cyclic |
| **P09** | 2.50 | 7.50 | 36 | 10.0 | 2-way multi-directional random cyclic |
| **P10** | 2.50 | 7.50 | 36 | 10.0 | 1-way uni-directional random cyclic |
| **P11** | 2.50 | 7.50 | 36 | 10.0 | 2-way uni-directional random cyclic |
| **P12** | 1.22 | 3.66 | 13 | 4.88 | 2-way multi-directional random cyclic |

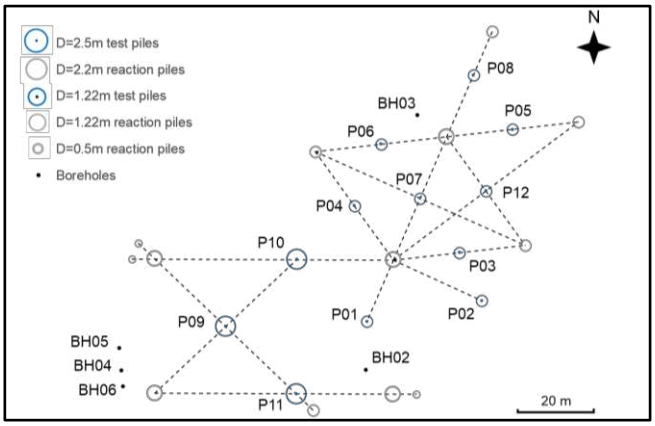


*Figure 2. Site layout.*

All the test piles were equipped with a set of transducers to determine their responses during each stage of the tests. The instrumentation consisted of linear displacement transducers (LDTs), load cells, biaxial stick-up inclinometers (SUIs), in-place inclinometers (IPIs), and fibre-optic strain and temperature gauges (using fibre Bragg gratings, FBGs). Vibrating wire piezometers (VWPs) were installed at 3 pile locations for the measurement of pore water pressure during all the test stages.

The LDTs were of magnetostrictive type and strokes of 75, 150, 300, 500, 750 and 1000 mm were used during the tests, selecting among these based on the displacement prediction for each test stage for ensuring the best displacement measurements resolution. A set of 4 LDTs per side (X+ & X-) at two different heights was installed for monotonic and uni-directional tests. A set of 12 LDTs was installed for the multi-directional tests, where 4 additional transducers were required for the Y+ and Y- directions, 2 for vertical displacement and 2 for the pile twist.

Except for P12, all piles were equipped with IPIs and FBGs. The medium diameter piles featured 2 strings of 8 IPIs and the large diameter piles had 2 strings of 12 IPIs, all installed on the X+ and X- pile sides. The IPIs were biaxial and capable of measuring the inclination also on the Y direction. Two strings of FBGs were installed on the medium diameter piles (on X+ and X- sides) and 4 FBGs strings were used for the large diameter piles (also on the Y+ & Y- sides).

VWPs were installed on 3 pile locations. 2 VWPs were installed at 2 depths for 2 of the medium diameter piles (P01 & P03) on the X+ side, whereas 8 VWPs (6 on the X+ & X- side, 2 on the Y+ & Y- side) were used on the large pile P09 at various depths.

Total station measurements were used to check and monitor the location of the main instrumentation during different test stages.

## 3.2 Test procedures

### 3.2.1 Test setup

Figure 3 shows the test set up for the medium diameter uni-directional cyclic tests, including a schematic of elevation and plan view. Both loading directions are indicated (X+ and X-) for these tests. For the monotonic tests on same diameter piles the sole loading direction X+ was used.

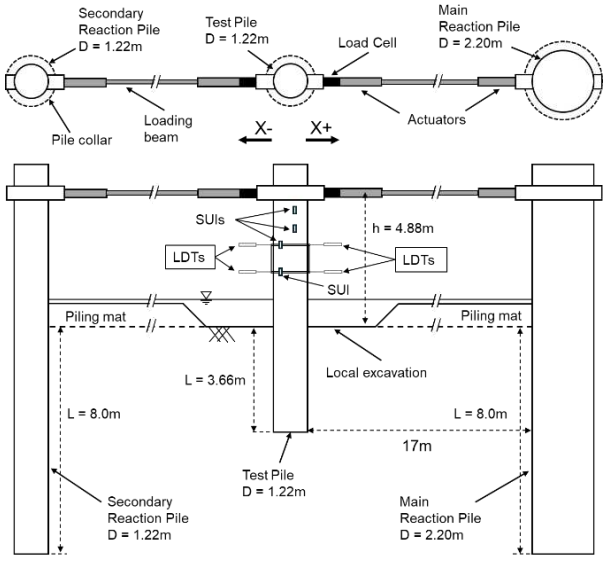


*Figure 3. Schematic for medium diameter uni-directional cyclic tests (P03-P06, P08).*

A schematic of both elevation and plan view for the multi-directional test on the large diameter pile P09 is shown in Figure 4. Two additional backstay reaction piles on the X direction were installed for providing additional support on the main loading direction. The ground level for each test pile coincided with that of a local excavation, which had a diameter equal to 2D around each pile to ensure the correct value of embedment depth and avoid the effect of the piling mat on the pile behaviour. Figure 5 shows a photo taken during the performance of the test on P09.

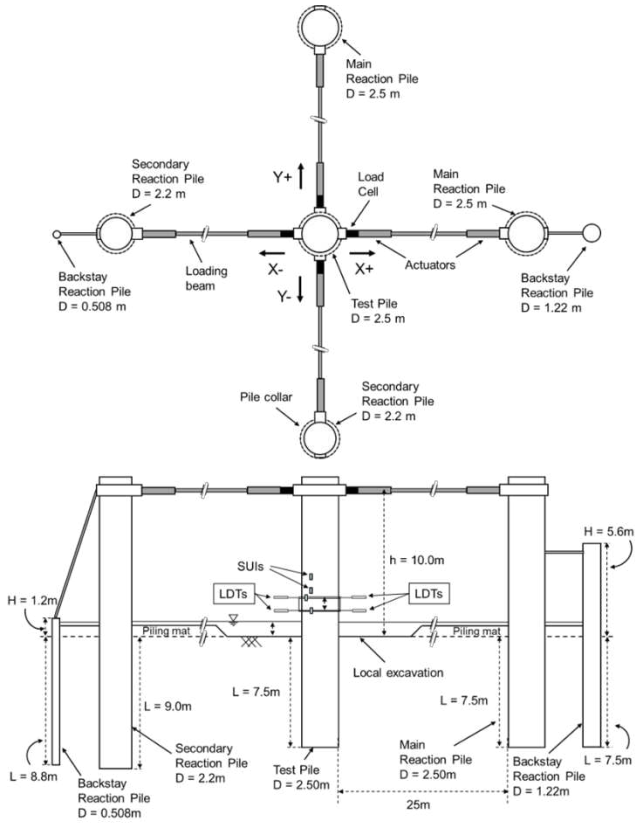


*Figure 4. Schematic for large diameter multi-directional cyclic test (P09).*

*Figure 5. 2-way multi-directional random cyclic test, P09.*

The LDTs were installed on a rigid instrumentation frame that was independent of the pile loading frame. LDT armatures were connected to a collar on the pile using UV joints to accommodate the vertical displacements of the corresponding pile sections. A weather cover was installed on each test pile prior to performing the tests to protect the instrumentation from the ingress of wind and water (Figure 5).

### 3.2.2 Monotonic and multi-rate monotonic loading

The monotonic test encompassed multiple stages of displacement-controlled loading. The ground-level displacement rate for all stages was fixed at D/300 per minute to minimise any influences of rate effects. In between the loading steps, the pile was allowed to creep by maintaining the current load until the creep rate became lower than 0.001% D per minute. After maintaining the load at the 3rd load increment, an unload-reload loop was conducted. The pile underwent unloading at a rate of D/500 to 10% of the previous maximum experienced load. The reload occurred at a D/300 rate. Once the reload was completed, the next loading increment was applied immediately after. The test ended by unloading the pile at D/500. Since no displacement instrumentation could be installed at ground level, the displacement rates and target values were estimated during the test using data from the lowest LDT on the X+ side.

The multi-rate monotonic loading started with the same 1st and 2nd loading increments as used in the monotonic test. After observing a similar initial stiffness, the test proceeded by an unload-reload loop. The 4th to the 9th loading increments were deliberately chosen as two packages of ground-level displacement rates in the order: 900 mm/min, 90 mm/min, and 0.9 mm/min. The approach enabled testing across three orders of magnitude in displacement rates. During the applied rate changes, variations in the response of the VWPs were recorded.

### 3.2.3 Uni-directional sinusoidal cyclic loading

Referring to the monotonic capacity at 0.1D ground level displacement, three cyclic load amplitudes were classified to construct low, medium and high phases of sinusoidal cyclic loads. The framework for the three sinusoidal cyclic loading tests consisted of a 24-hour low-loading phase, a 12-hour medium-loading phase and a high-loading phase lasting until a target ground-level displacement was reached, permitting enough cycles to observe ratcheting evolution under high loads. The three sinusoidal tests were:

- 1-way, loading between 0 & $H_{max}$
- 1.5-way, loading between -$H_{max}/2$ & $H_{max}$
- 2-way, loading between -$H_{max}$ & $H_{max}$

where $H_{max}$ is the maximum load for each phase. A monotonic stage was performed after each test.

### 3.2.4 Uni-directional random cyclic loading

As for the sinusoidal cyclic loading, the same low, medium and high-loading amplitudes were used to build the framework for the pseudo-random patterns applied. The patterns built for both Cowden and Cuxhaven represent those applied to a real offshore turbine at different operational and environmental stages. These tests also started with 24 hours of low-loading cycles, followed by 12 hours of medium amplitude cycles. Diverging from the sinusoidal tests, the high storm loading pattern lasted up to 3 hours with varying frequency and structure of the cyclic loading. The cyclic parts of the tests concluded with a span of 2 to 6 hours of medium cyclic loading terminated when the displacement changes were negligible. Three tests of this type were conducted: two 2-way tests on a medium and large diameter pile, respectively, and a single 1-way test on a large pile.

### 3.2.5 Multi-directional random cyclic loading

The multi-directional random cyclic loading tests followed the same framework as the 2-way uni-directional random tests in the X direction as a baseline for checking the impact of the orthogonal loads. Contemporaneously, a smaller magnitude random loading was applied in the Y direction. One of the resulting cyclic loading patterns is shown in Figure 6. The multi-directional random loading tests were performed on two medium diameter piles and one large diameter pile for scaling purposes.

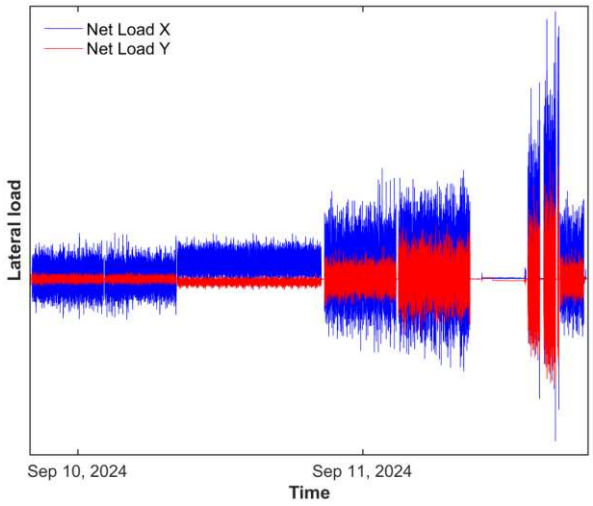


*Figure 6. Timeseries of the multi-directional random cyclic loading scheme applied to P12.*

## 4 RESULTS

### 4.1 Monotonic results

The monotonic test results confirmed the observations from monotonic tests conducted at campaigns such as the PICASO clay site and PISA. Creep was observed at the load hold periods, while each loading increment initially showed a steep increase in stiffness with the response eventually returning to the backbone curve.

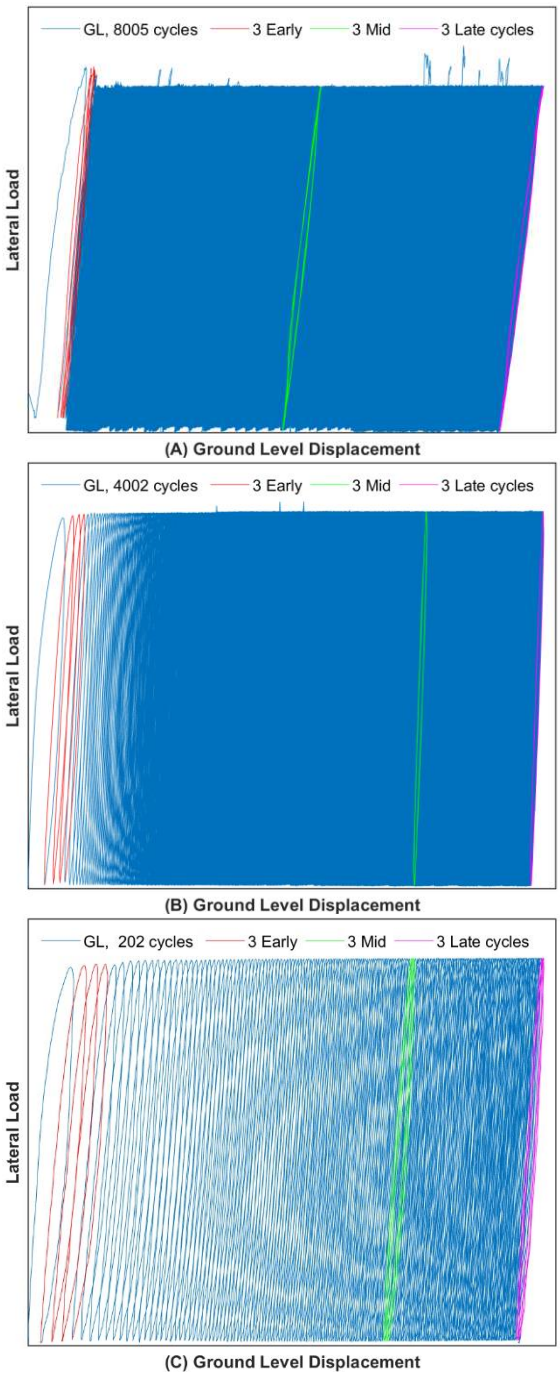


*Figure 7. Lateral load vs ground level displacement (GL) for uni-directional sinusoidal one-way loading. (A) low load, (B) medium load, and (C) high load. Three early, middle, and late cycles are highlighted for every load stage.*

### 4.2 Cyclic results

Figure 7 illustrates the ground level displacement of pile P04 subjected to low, medium and high amplitude sinusoidal one-way cyclic loading. Compared to tests at the PICASO clay site in Martin et al. (2023), the

hysteretic energy loss per cycle, normalised by loading magnitude and permanent deflection, is smaller at all load severeness levels. A stiff response and fairly closed hysteresis loop can be inferred at the low load levels. As the load increases, the hysteresis loops open and ratcheting intensifies. Figure 7, by identifying a different relative position of the three middle cycles for (A), (B) and (C), indicates that the ratcheting evolution functions vary for the different load levels.

Figure 8 compares the bending moment profile below ground level at the final peak of each cyclic load stage for P04. All profiles are generated by discretising the pile into Timoshenko beam elements, applying a boundary condition with the base moment set to zero for simplification. Medium and high cyclic moments show similar distributions and peaks, while the low cyclic peak moment occurs at a greater depth. The below ground results align with the PICASO clay site and may be affected by the number of cycles per stage.

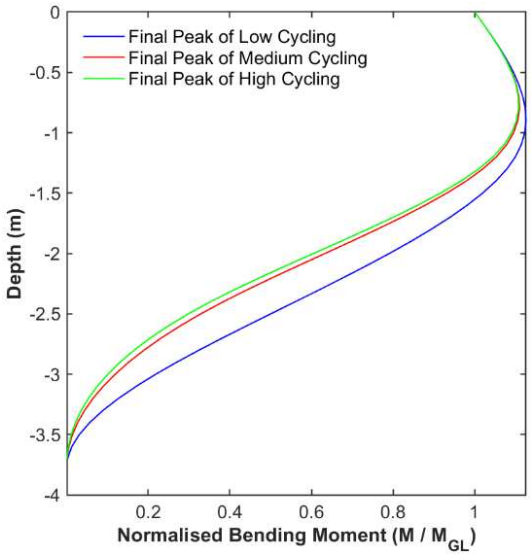


*Figure 8. Normalised bending moment at the final peak of each stage for uni-directional sinusoidal one-way loading.*

## 5 CONCLUSIONS

This paper presents details of field-testing at Cuxhaven, the PICASO sand test site, including preliminary results. The main results are aligned with the findings from the PICASO clay site and PISA regarding the monotonic loading. The cyclic results also show some trends similar to that observed for the cyclic tests at the PICASO clay site, in particular:

- Cycles became more open and ratcheting increased for larger loads applied;
- The profiles of bending moment with depth show that the pile behaviour remains relatively similar for different load levels.

The results and data collected during the PICASO sand campaign, along with those collected for the clay site testing, will form the basis for new design methods for lateral cyclic loading of monopiles in the future.

## AUTHOR CONTRIBUTION STATEMENT

**Byrne**: Conceptualisation, Supervision, Methodology, Reviewing. **Nardelli & Rasmussen:** Data curation, Formal Analysis, Writing-Original draft. **Vaitkune:** Reviewing. **Cameron, Crook, Kragelund, Shonberg, Soares Cunha & Turner**: Resources. **All Authors**: Investigation.

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## REFERENCES

Byrne, B.W. (2020). Editorial: geotechnical design for offshore wind turbine monopiles. Géotechnique, 70(11), pp. 943-944. doi:10.1680/jgeot.2020.70.11.943

Byrne, B.W., McAdam, R.A., Burd, H.J., Beuckelaers, W.J.A.P., Gavin, K.G., Houlsby, G.T., Igoe, D.J.P., Jardine, R.J., Martin, C.M., Muir Wood, A., Potts, D.M., Gretlund, J.S., Taborda, D.M.G., Zdravkovic, L. (2020). Monotonic laterally loaded pile testing in a stiff glacial clay till at Cowden. Géotechnique, 70(11), pp. 970-985. doi:10.1680/jgeot.18.PISA.003

Hardin, B. O. (1978). The nature of stress–strain behaviour for soils. *Proceedings of the ASCE Geotechnical Engineering Division specialty conference*, Pasadena, CA, USA, Vol. 1, pp. 3–90.

Houlsby, G.T. and Puzrin, A.M. (2006). Principles of Hyperplasticity. London, UK, Springer-Verlag.

Knudsen, S., Lunne, T., Quinteros, V.S., Vestgården, T. Krogh, L. and Bøgelund-Pedersen, R. (2019). Effect of reconstitution techniques on the triaxial stress-strength behaviour of a very dense sand. Proceedings of the XVII ECSMGE.

Martin, S.C., Buckley, R.M., McAdam, R.A., Lindeboom, R., Byrne, B.W., Wu, K., Turner, S. and Cameron, A. (2023). Medium-scale field testing of laterally loaded monopiles in glacial till at Cowden. Proceedings of the 9th International SUT OSIG Conference, London, UK. Pp. 595-602. doi.org/10.3723/PKFE5118

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., Gretlund, J.S., Taborda, D.M.G., Zdravkovic, L. (2020). Monotonic laterally loaded pile testing in a dense marine sand in Dunkirk. Géotechnique, 70(11), pp. 986-998. doi:10.1680/jgeot.18.PISA.004

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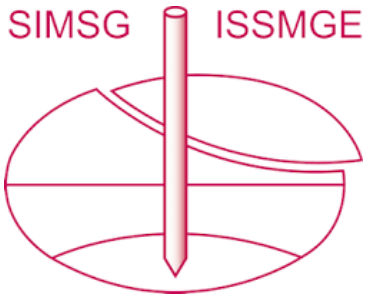


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