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# Monopiles under cyclic loading: First results from the Ho-Pile project

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**ABSTRACT:** The efficient and economical design of support structures for offshore wind turbines continues to pose significant challenges to the industry. The approaches currently used for designing monopiles under cyclic loads lack experimental evidence from large-scale tests. Within the research project Ho-Pile, the Fraunhofer Institute for Wind Energy Systems and the Leibniz Universität Hannover investigate the applicability of design approaches for offshore monopiles by means of large-scale cyclic testing. This paper summarises the first results of the preliminary test on a model pile with a diameter of 0.914 m and an embedded length of 6.15 m. The main aims of the test were to confirm the measuring concept's efficacy and to assess the actuator's capabilities. The model pile was impact-driven into artificially prepared, densely packed, non-cohesive soil. The test programme includes 16 consecutive load packages with 15,100 cycles with different load characteristics. The pile load-deflection curves and the soil's pore pressure evolution are shown and discussed. A first attempt to adopt an existing empirical method to predict the experimental accumulated monopile displacement was encouraging. The monitoring concept was deemed appropriate for the Ho-Pile main testing phase.

**Keywords:** monopiles, large-scale tests, cyclic loading, accumulated deformation.

## 1 INTRODUCTION

### 1.1 Motivation and Background

The UN Climate Change Conference of 2021 in Glasgow confirmed the 1.5°C target from the Paris Climate Agreement. Additionally, all states should gradually reduce the use of coal-fired power plants without carbon capture technologies (IPCC, 2021). With an actual coverage of 16% of the overall electrical demand in Europe, the use of onshore and offshore wind energy is a significant alternative energy source. According to WindEurope (2021), monopiles are still the predominant support structures for offshore wind farms in Europe with a market share of around 80% in 2020. Due to greater water depths and increasing turbine dimensions, current monopiles have a diameter, $D$, up to 10 m and a pile length to diameter ratio, $L/D$, less than six. Consequently, their load-bearing behavior can be classified as relatively rigid, implying an early activation of the pile toe compared to long slender piles used for the oil and gas industry.

To predict their monotonic and cyclic load-bearing behavior, the original used p-y design method from the oil and gas industry seems not to be compatible without any further validation (DNV, 2016). To tackle this issue, in the last years, several numerical and physical studies have been undertaken, resulting in different method adaptations for the prediction of the monotonic load-bearing behavior (Byrne et al., 2019; Spill et al. 2020). The cyclic design approach proposed by DNV (2016) adopts a general capacity reduction factor, $A = 0.9$, which does not consider load characteristics and the number of cycles. In addition, the approach was validated on slender pile systems for a maximum of 100 cycles, which corresponds neither to the load history nor to the geometry of today's monopiles. Several approaches have been developed to improve the design methods for long-term cyclic loading, which can be classified as empirical and numerical. As for the latter the stiffness degradation method (SDM) (Achmus et al., 2009) and the high-cycle accumulation (HCA) method (Staubach et al., 2021) are two well-known examples. The SDM, for instance, is based on cyclic triaxial laboratory tests and enables the prediction of the relative increase of the head deformation of a horizontally cyclically loaded pile. As for the empirical approaches, they can predict the cyclic pile head displacement or rotation after a certain number of load cycles on the base of simple equations and empirical parameters, often calibrated with small-scale tests (LeBlanc et al., 2010).

### 1.2 The Ho-Pile Project

Regardless of the cyclic loading design approach considered, a comprehensive validation against realistic experimental results is lacking. The Ho-Pile project aims to gain further knowledge about the cyclic load-bearing behavior of monopiles and to provide additional large-scale test data for current and future generation monopiles. Ho-Pile was developed by the partners Leibniz University of Hanover (LUH) and Fraunhofer IWES. Within the project, six large-scale tests are carried out in the foundation test pit of the Test Centre for Support Structures Hanover, a test facility of the LUH. The foundation test pit is an indoor sand pit measuring 14 m (length) by 9 m (width) by 10 m (depth), where large-scale model tests of foundations can be performed in a fully controlled, artificially prepared testing environment. In the primary test campaign, two pile systems with diameters of 1.52 m and 0.914 m and an embedment depth of 6.15 m will be tested. Prior to the primary campaign, a preliminary test was planned with the following specific aims:

- Check the reliability of the monitoring concept;
- Qualitatively evaluate the loading frequency dependency of the pore pressures around the pile while loading cyclically;
- Observe whether the soil plug occurred during and at the end of the pile installation;
- Evaluate the capability of the actuator with respect to the designated frequencies and load magnitudes.

In this contribution, the Ho-Pile preliminary test is described, and its results pertaining to the aims above-mentioned are presented and discussed.

## 2 DESCRIPTION OF THE TEST

### 2.1 Soil Preparation and Test Set Up

The soil material consists of uniformly graded silicious sand named Rohsand 3152. Its physical properties are listed in Table 1. Note that $e_{\max}$, $e_{\min}$ and $Gs$ were reassessed in 2020 and marginally diverged from previously published data. The sandy material was distributed in layers of around 25 cm until an overall height of 9.5 m was reached. For each layer, the sand was equally distributed across the pit surface, compacted, and sampled with three core samples. During installation and testing, the water table was set slightly above the sand surface by means of a drainage layer at the bottom of the pit. The extracted core samples revealed a relative density, $D_r = 0.62$, and a variation coefficient of 6.7%.

Table 1. Physical properties of the test sand Rohsand 3152 as reassessed in 2020.

| Property | Unit | Value |
|---|---|---|
| Maximum void ratio, $e_{\max}$ | - | 0.82 |
| Minimum void ratio, $e_{\min}$ | - | 0.41 |
| Specific gravity, $G_s$ | g/cm$^3$ | 2.61 |
| Coefficient of uniformity, $C_u$ | - | 1.82 |
| Coefficient of curvature, $Cc$ | - | 0.96 |
| Grain diameter to 60% passing material, $D_{60}$ | mm | 0.40 |

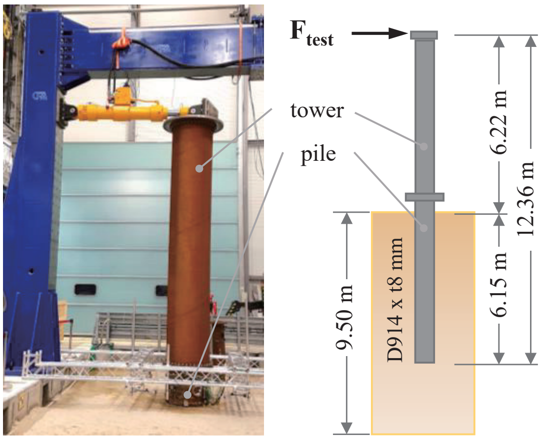

Fig. 1. Test set up of the preliminary test.

These results reflect homogenous dense sand conditions and are similarly replicated in the primary campaign. Cone penetration tests prior to the pile installation, not shown here for brevity, confirmed the homogeneity and packing state of the sand. For the preliminary test (see Figure 1), here called D914, a hollow steel pile with a total length of 6.85 m, embedded length, $L$ = 6.15 m, wall thickness, $t$ = 8 mm, and diameter, $D$ = 0.914 m, was impact driven into the foundation test pit employing a double-acting hammer Menck SB 270. The cyclic horizontal force was applied with a hydraulic actuator (maximum capacity of 500 kN) featuring a load cell used to control and record the applied loading. To apply the necessary bending moment, the actuator was fixed between the loading frame and a steel tower, which was bolted to the pile head flange. Depending on the prototype specifics, the model scale is approximately between 1:6 to 1:10.

### 2.3 Measurement Concept

The Ho-Pile measurement concept comprises sensors in the soil and on the pile. The soil is instrumented with pore water and total earth pressure transducers at various depths. The pile monitoring concept aims at measuring pile deflection and rotation throughout the pile embedded length. Strain gauges are placed every 0.5 m along the pile length on both sides of the loading direction. As protection against moisture and mechanical damages, the strain gauges were covered with protective resins. The pile rotation as a function of depth is measured utilizing two inclinometer chains with measuring rates of 0.017 Hz (Chain01) and 20 Hz (Chain02). Chain01 was already successfully used in previous projects featuring quasi-static loading and is used in Ho-Pile as a redundant measure. Chain02 was put into operation for the first time in the Ho-Pile project and was necessary to analyze the details of the deflection behavior during the load cycles. The chains are installed after the pile installation into inclinometer tubes arranged inside the pile in 90 degrees with respect to the strain gauge position. To derive the deflection line and the load displacement behavior at ground level, displacement transducers are arranged at different levels at each pile side.

### 2.3 Test Program

To achieve the aims outlined in Section 1.2, the loading program shown in Table 2 was developed. It consisted of three one-way loading blocks. Each block starts with a monotonic loading and unloading phase (Section A) and is then followed by five cyclic phases (Sections B to F), each containing 1000 cycles. In Table 2 $\zeta_c$ is the loading characteristic referring to the load asymmetry introduced by LeBlanc et al. (2010), $H$ is the maximum load reached within a section, $f$ is the loading frequency, and $N$ is the number of cycles. From Section B to F the frequency $f$ is variated (0.1, 0.2, 0.4, 0.8 and 1 Hz) maintaining a value of $\zeta_c = 0.33$. The cyclic mean load of each cyclic section corresponds to the maximum load $H$ of the previous monotonic section and is increased with each block. At the end of Block 3, a sixth section G with $\zeta_c = 0$ and $N = 100$ was additionally executed.

Table 2. Loading program for test D914.

| Block | 1 | | 2 | | 3 | | |
|---|---|---|---|---|---|---|---|
| Section | A | B - F | A | B - F | A | B - F | G |
| $\zeta_c$ (-) | - | 0.33 | - | 0.33 | - | 0.33 | 0.0 |
| $H$ (kN) | 32.0 | 48.0 | 68.0 | 100.0 | 109.0 | 173.0 | 218.0 |
| $f$ (Hz) | - | 0.1-1.0 | - | 0.1-1.0 | 100 | 0.1-1.0 | 0.2 |
| $N$ (-) | - | 5x1000 | - | 5x1000 | - | 5x1000 | 100 |

## 3 RESULTS OF THE TEST

### 3.1 General Remarks

The pile was installed without major complications to its final depth (6.15 m). An optical measurement after the installation revealed no formation of plugging. All monotonic loading sections could be carried out according to the loading program. Turning to the cyclic loading sections, an increasing deviation from the designated maximum and minimum loads with increasing frequency and load amplitude was observed for all the sections except those with the lowest frequency (Sections B, $f$ = 0.1 Hz). Despite the mentioned amplitude deviation, the designated mean load levels were maintained except for load sections 3C and 3G, which showed a discrepancy of -4.5% and -18%, respectively.

The analysis of the collected data yielded satisfactory results for the pore water and earth pressures, for the displacement measurements and for the strain gauges. Moreover, a comparison of the data from the inclinometer chains revealed plausible results for both measuring systems. As in Figure 2 exemplary shown, Chain02 tends to overshoot when the maximum or minimum load is reached, especially in loading sections with high loading frequency. However, using a binominal filter helps smooth the recording by eliminating noise and unrealistic peaks.

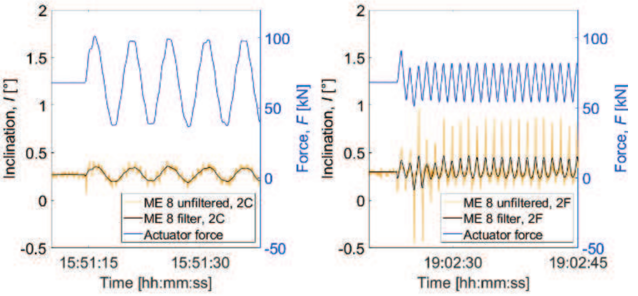

Fig. 2. Block 2 unfiltered (orange) and filtered (black) inclinometer Chain02 behavior at 0.2 Hz (left) and 1.0 Hz (right) and corresponding load (blue).

### 3.2 Pore Pressure Analysis

The development of pore water pressure, $u$, was measured at depths of 0.45 m (PWD1), 1.8 m (PWD2) in front of the pile and at a depth of 5.85 m (PWD3) behind the pile. As Figure 3 exemplary shows, all sensors indicated a moderate increase in pore pressure until the mean load, here 68 kN, was reached. This is particularly visible for PWD3. In correspondence to the unloading phase of the first cycle of PWD1 and PWD2, a visible jump in the negative sector of the diagram can be noted. Its effect seems, however, to decrease as the test proceeds further and, after a few load cycles, the pore pressure stabilizes around a fixed mean. As far as the pile toe sensor (PWD3) is concerned, a small pore water pressure accumulation seems to occur throughout the cyclic loading sections, regardless of the loading frequency. This can be attributed to the more restrained drainage path at pile toe as compared to that at the pile head. At the end of each cyclic section, the pore water pressure returns to its original value, as expected.

### 3.3 Load Displacement Analysis

To derive the load-displacement curve at ground level, the displacements measured 10 cm above the ground are averaged and then transferred using the inclinometer results. The curve is visualized in Figure 4 and indicates

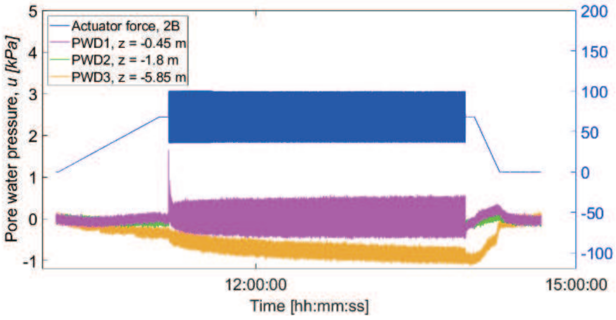

Fig. 3. Pore water pressure development in section 2B.

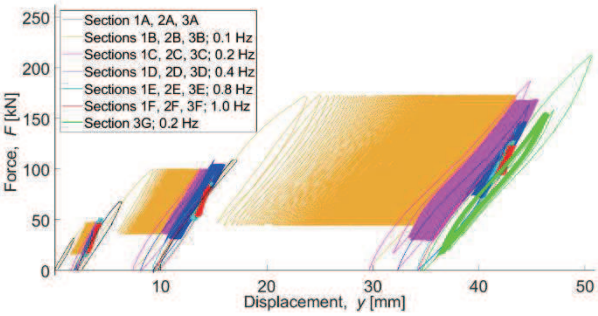

Fig. 4. Load displacement curve at ground level after the subtraction of creep deformation at zero force.

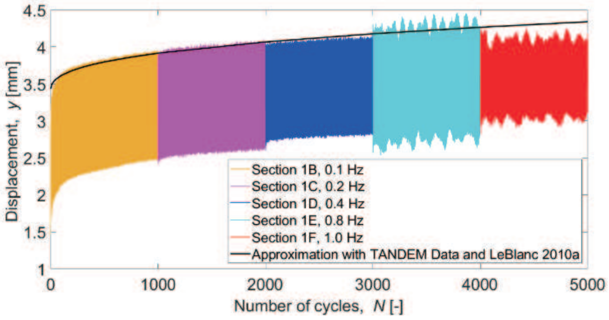

Fig. 5. Comparison between results of Block 1 and a calculation with the approach by LeBlanc et al. (2010).

the typical nonlinearly decreasing displacement rate. Moreover, a permanent displacement of 34.7 mm at the end of the test and 9.8 mm and 2.1 mm after the second and the first Block, respectively, can be observed.

Interestingly, in Figure 5 it can be noted that the accumulated displacement of Block 1 reveals no significant effects due the loading frequency changes, especially until Section D. However, during Sections E and F the displacement rate seems to damp, probably also due to the high loading frequency. A first comparison with the prediction method of LeBlanc et al. (2010) and input data from the TANDEM project (Spill et al. 2020), reveals reasonable agreement, although the monotonic displacement is underestimated by 0.4 mm. Note that contrary to the original LeBlanc-approach, here, different loading frequencies are superposed, the sand is saturated, and the displacement − and not the rotation − is calculated.

## 4 SUMMARY AND CONCLUSION

Within the research project Ho-Pile, the cyclic load-bearing behavior of monopiles is being investigated using large-scale tests. The paper's preliminary test results show that all sensors worked as planned and the measurement concept appears suitable for the primary Ho-Pile campaign. As the actuator seems to have difficulty in reaching large load amplitudes at high frequencies, it is advisable to optimize the controlling parameters before carrying out the primary campaign. An analysis of the pore water sensors indicates slight accumulation due to cyclic loading at the pile toe. Conversely, at pile head, the water pressure cycles along with the loading without accumulating. As could be expected for foundations in water-saturated sand, the pore water pressure returns quickly to the hydrostatic value at the end of each load section. A first comparison of the load-displacement behavior at ground level for the initial loading block with the method proposed by LeBlanc et al. (2010) revealed promising results. Its applicability, as well as the methods from other authors will be further investigated through the results from the main campaign.

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