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Experimental investigation of the installation and lateral capacity of instrumented monopiles at the SAGE-SAND test site in Zeebrugge

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ABSTRACT: Research project SAGE-SAND explores the potential of vibratory driving for the installation of monopile foundations, commonly used for offshore wind turbines. Within the frame of this project, a full-scale test campaign is conducted, which involves the driving and extraction of four instrumented steel piles with a diameter of 2 m and a length of 21 m, as well as lateral load tests on these piles to experimentally determine the lateral capacity and investigate ageing effects. The test campaign is performed on a test site in Zeebrugge, Belgium. This paper provides a detailed overview of the planned experiments, including the experimental setup of the lateral load tests and the corresponding sensor layout. The installation of the piles and the subsequent first lateral load tests were initiated at the beginning of 2025.

Keywords: Vibratory driving, Soil ageing, Pile driving analysis, Lateral load test, Validation

1 INTRODUCTION

Offshore wind turbines (OWTs) are rapidly growing in size. As a result, larger foundations are required to safely take up higher external loads, limit structural deformations, and ensure proper operation of the OWTs during their lifetime, which includes exposure to a harsh operational environment. Nowadays, the majority of the OWT foundations consists of monopiles (large diameter hollow steel piles), which are commonly installed by impact driving. This installation technique comes with two major drawbacks: 1) the pile driving generates high levels of underwater noise, which impacts marine life (Bailey et al., 2010) and 2) the driving induces high stress levels in the pile, which consumes part of the fatigue lifetime of the foundation and therefore reduces the operational lifetime of the OWT (Orlando et al., 2023).

Vibratory pile driving is an alternative technique which is often applied onshore. It has multiple advantages over impact driving (Saleem, 2011):

1) Typical installation times in sandy soils are 3 to 4 times lower.
2) It comes with a lower installation cost, since the installation is faster and uses less energy.
3) Noise emissions are significantly lower.
4) The pile handling is simplified, since the pile is directly clamped by the vibratory hammer, enabling to skip the step of aligning the pile and placing the hammer at the start of the installation process.
5) The fatigue due to pile driving is much lower, which increases the lifespan of the monopile foundation.
6) It allows not only for pile installation but also for pile decommissioning.

Vibratory pile driving has recently attracted interest for offshore applications, where the load bearing capacity and the dynamic response of the OWT are driving the foundation design. However, mainly due to ambiguity in soil-pile interaction, the application of vibratory pile driving in offshore engineering practice so far is very limited.

In contrast to impact driving, vibratory driving commonly induces liquefaction in the soil surrounding the pile (Holeyman, 2002). The liquefaction potential and the extent of the liquefiable zone are presently not well understood, in particular in an offshore context. Furthermore, it is expected that liquefaction affects the short-term and potentially the long-term soil stiffness and therefore the lateral behavior and the fatigue lifetime of the OWT under operational conditions, where it is also know that cyclic loading processes affect foundation stiffness.

Field tests conducted after pile installation have shown a significant increase of the shaft capacity against axial loading and soil stiffness over time (Jardine et al., 2006). This ageing effect is attributed to mechanical changes through particle rearrangements and chemical changes in the liquefied soil surrounding the pile. Research project SAGE-SAND, funded by the Energy Transition Fund (ETF) of the Belgian Government, aims to provide a combined experimental and theoretical investigation of this hypothesis, particularly with focus on the lateral resistance of the monopile foundation. The project involves following academic partners: KU Leuven, UC Louvain, and ULiège.

The SAGE-SAND project entails a number of theoretical developments and experimental investigations and is subdivided in four work packages: 1) “Large-scale pile tests and monitoring”, 2) “Sediment and micromechanical characterization”, 3) “Micromechanical modeling”, and 4) “Macroscale modeling”. This paper fits within the first work package, which aims to experimentally investigate the effect of soil ageing on the lateral behavior of monopiles installed by both impact and vibratory driving, through a combination of lateral load tests, repeated CPT testing inside and outside the piles, and repeated dynamic soil characterization tests.

The experimental investigation is performed on a test site that has been selected at the Port of Zeebrugge (Figure 2). For this site, the soil conditions are very similar to those encountered in offshore wind turbine (OWT) parks in the Belgian North Sea. A detailed overview of the geotechnical characterization of a test site is found in (Letitzia et al., 2024).

The structure of the paper is as follows. Section 2 first provides an overview of the pile installation process and the lateral load tests. Next, Section 3 discusses the instrumentation of the four monopiles and the test site for the analysis of the pile driving, the lateral load tests, and the monitoring of the soil ageing process. Finally, Section 4 concludes the paper and provides an outlook.

Figure 2. Situation of the test site for the large-scale pile tests in the Port of Zeebrugge.

2 PILE INSTALLATION AND LATERAL LOAD TESTS

Figure 1 provides an overview of the pile configuration. Six collinear pile locations are considered, separated by an intermediate distance of 15 m. Those locations are covered by four instrumented piles (P1 – P4), each with an outer diameter (D) of 2 m and a length (L) of 21 m. The wall thickness (t) varies between 17 and 48 mm. The pile driving is performed in four stages, which are discussed in detail in the following sub-sections.

2.1 Stage 1

<u>Pile driving</u> – In the first stage, the four piles (P1 – P4) are driven at locations V1, I1, V2a and I2a, respectively (Figure 1). The piles at locations I1 and I2a are impact driven, those at locations V1 and V2a are vibratory driven. Prior to the impact driving, piles P2 and P4 are first vibratory-driven up to a penetration depth of about 5 m, in this way making them auto-stable. Next, the impact hammer is mounted and the impact driving process is initiated. The impact driving is performed using an S-200 IQ Hydrohammer. The vibratory driving is performed using a PVE 150M vibratory hammer. Both for impact and vibratory driving, the target depth is 17 m.

<u>Lateral load tests</u> – Following the pile driving, piles P3 and P4 (at locations V2a and I2a) are

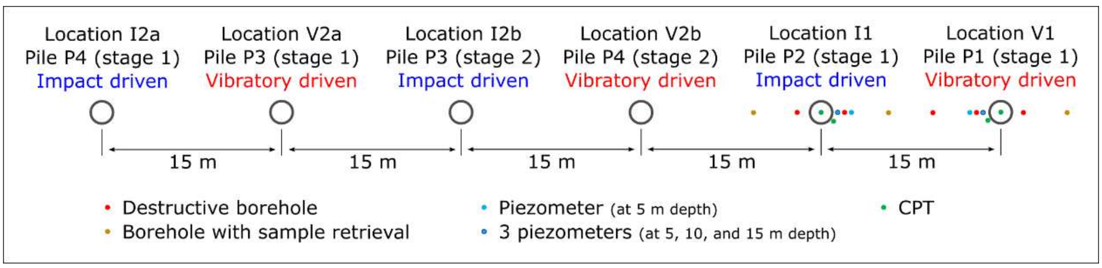

Figure 1. Overview of the pile configuration, with indication of the borehole, CPT, and piezometer locations.

subjected to a lateral load test with multiple unloading-reloading phases. This test aims at (1) the determination of the upper limit of the lateral capacity of the pile (noted F_u [MN]), for which the lateral displacement u at the mudline is $0.1D$, and (2) the investigation of the unload-reload levels that are the be applied in a later stage. The loading scheme is schematically represented in Figure 3.

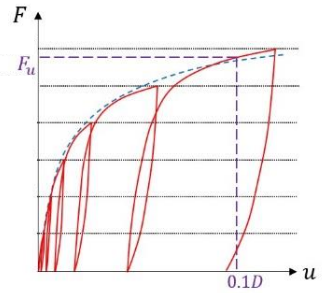

Figure 3. Schematic representation of the loading scheme (lateral force F versus lateral displacement u) for the determination of the lateral capacity F_u.

The lateral load tests involve a custom-made load frame, depicted in Figure 4. This consists of two individual steel reaction frames that are connected through a series of steel rods, similar to the load frame presented in (Achmus et al., 2020). During the lateral load tests, the two piles are pulled together by hydraulic jacks at the back of the reaction frames (green cylinders in Figure 4). The applied lateral load F is measured using load cells connected to the hydraulic jacks. The change in distance between two consecutive piles and with respect to a fixed point in the environment is measured using a combination of wire-rope displacement sensors and a telemeter laser. In addition, the bending moments along the length of the monopiles are measured using distributed fiber-optic sensing, as discussed hereafter in Section 3.

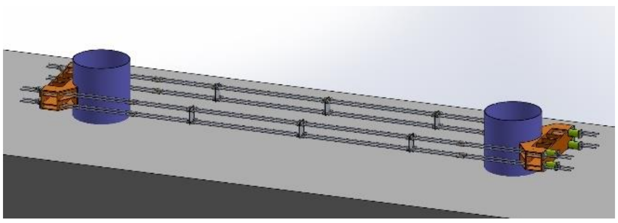

Figure 4. Drawing of the lateral pile loading system.

Once F_u has been experimentally determined, piles P1 and P2 (at locations V1 and I1) will be subjected to a monotonic lateral loading with three unload-reload phases at respectively five, ten, and twenty percent of the previously determined F_u, as schematically represented in Figure 5.

<u>Extraction of piles P3 and P4</u> – After completion of the first load tests, piles P3 and P4 will be removed by means of vibratory driving.

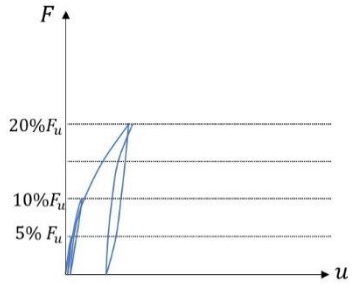

Figure 5. Schematic representation of the loading scheme (lateral force F versus lateral displacement u) for the cyclic lateral load tests up to $20\%F_u$.

<u>Re-installation of piles P3 and P4</u> – Piles P3 and P4 are re-installed by respectively impact driving and vibratory driving at locations I2b and V2b, see Figure 1. Notice that the order of the piles has been reversed (pile P3 was first vibratory driven and is now impact driven and vice versa for pile P4).

2.2 Stage 2

<u>Low intensity lateral load tests on both pairs of piles</u> – Six weeks and six months after the end of stage 1, both pairs of piles (P1 with P2 and P3 with P4) are subjected to the loading scheme at low loads presented in Figure 5.

2.3 Stage 3

<u>Lateral load tests up to failure on both pairs of piles</u> – After 1 year, the two pairs of piles are tested up to failure, following the loading scheme presented in Figure 3.

<u>Additional cyclic lateral load tests, including unloading-reloading</u> – Piles P2 and P4 (respectively at locations I1 and V2b) are now subjected to additional cyclic lateral loading, including unloading and reloading. The unloading involves lateral loading of piles P2 (I1) and P4 (V2b) against each other. The reloading involves lateral loading of pile P1 (V1) against P2 (I1) and P3 (I2b) against P4 (V2b), see Figure 6.

<u>Extraction of all piles</u> – After the completion of the cyclic lateral load tests, all piles are removed by means of vibratory driving.

3 SENSOR LAYOUT

In this section, three different types of measurements are considered. First, Subsection 3.1 discusses the measurements of the pile response during the pile driving. Next, Subsection 3.2 describes the distributed strain sensing to measure the pile bending during the lateral load tests. Finally, Subsection 3.3

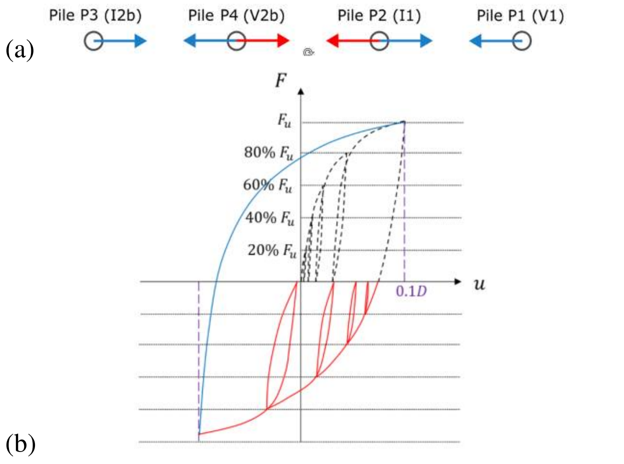

Figure 6. Overview of the cyclic lateral unloading and reloading in stage 3.

provides details on the dynamic pore water pressure measurements in the direct vicinity of piles P1 and P2 (see Figure 1).

3.1 Measuring pile response during driving

The pile instrumentation is visualized in Figure 7 for pile P3. This is the most heavily instrumented pile, equipped with shock accelerometers (Section 3.1.1), FBG strain sensors (Section 3.1.2), thermocouple sensors (Section 3.1.3), distributed fiber-optic strain sensors (Section 3.2.1), and calendaring marks.

3.1.1 Shock accelerometers

Two shock accelerometers of the type PCB 350C03 (sensitivity 0.5 V/g, ±10 000 g pk) will be mounted on a steel mounting base that will be bolted to the pile at a distance of 3.5 m below the pile top. The two accelerometers are installed diametrically opposite to each other. They measure in the vertical direction and are key in the pile driving analysis (PDA).

3.1.2 FBG strain sensors

The dynamic pile deformation induced by the driving is captured using fiber Bragg grating (FBG) strain sensors that are spaced along the length of the pile (Figure 7). For this, two of the four piles (P3 and P4) are equipped with two strings of 18 FBG sensors. The strings consist of a 1 mm GFRP coated fiber which is routed from the top of the pile to the bottom and back up. The individual FBG sensors have an intermediate distance of 2 m. The fibers are embedded in a groove with a width of 2 mm and a depth of 3 mm, which is cut in the pile along its length using a plunge saw and an angle grinder. The fiber is glued using epoxy glue of the type Araldite 2021-1. At the bottom of the pile, where the fiber curves and is horizontal, the fiber is protected by means of a 5 mm thick steel plate that is welded to the pile (Figure 7).

3.1.3 Thermocouple sensors

The aim of the temperature measurements is two-fold. During the installation and decommissioning of the piles, they capture heating that arises from friction and which is expected to affect the chemical and ageing processes in the soil. Second, they will capture the temperature profile in the soil, which is used for temperature compensation of the quasi-static strain measurements during the lateral load tests.

Only pile P3 is equipped with type T thermocouple sensors. The location of these sensors is indicated in Figure 7 (TC). Since temperature fluctuations in the soil over the year are mostly limited to the first 10 meters below the surface level, the majority of the thermocouple sensors are located in the top part of the pile. The bottom thermocouple, i.e. TC8, is located at 1 m above the pile tip. Similar to the optical fiber sensors, the thermocouple sensors

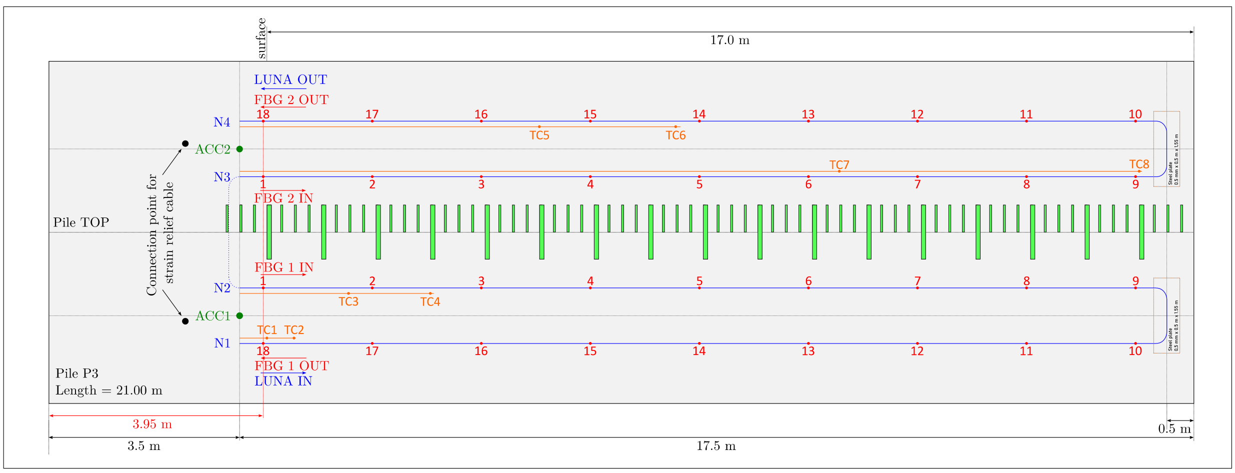

Figure 7. Overview of the measurement setup of pile P3, with indication of the accelerometers (ACC) locations, the fiber routing (FBG and LUNA), the thermocouple (TC) locations, and the calendaring marks (green).

are embedded in a vertical groove and glued using epoxy glue of the type Araldite 2021-1.

3.1.4 Data acquisition

The acceleration, FBG strain, and thermocouple measurements are performed synchronously. For the acceleration and strain measurements, a sampling rate of about 10 kHz is adopted, in order to capture phenomena related to wave propagation in the steel monopile during the pile driving. The temperatures will be sampled at a lower sampling rate of 68 Hz, which is sufficient to capture local heating that arises from the pile driving.

3.1.5 Strain relief mechanism

During the pile driving, a flexible strain relief mechanism is used to prevent damage of the fibers and cables routed from the pile top towards the data acquisition system. This consists of a steel cable which is connected about 2.5 m below the pile top using a rubber band (connection point indicated in Figure 7). This flexible connection cancels out the vibration of the driving process and avoids severe shock loading of the steel cable, to which all fibers and sensor cables are strapped.

3.1.6 Calendaring system

Position indicators will be painted along the length of the four piles, see Figure 7. Those will be used to track the driving process by means of calendaring. We will use a video camera that is installed at a sufficiently large distance from the pile center, as to ensure a full view of the pile and to avoid an influence of the pile driving on the video capturing.

3.1.7 Soil plug level measurements

At the end of the pile driving, the level of the soil plug inside the piles will be measured (1) relative to the level outside the piles and (2) relative to the level of a fixed point in the environment. These measurements will be performed using a Leica laser level meter.

3.2 Measuring pile response during load tests

3.2.1 Distributed fiber-optic strain sensors

All four piles are equipped with distributed fiber-optic strain sensors (DFOS), since these measurements are key to keep track of the moment distribution in the piles during the lateral load tests. The strain measurements will be performed by means of a Luna interrogator, using the Rayleigh backscatter principle. In order to enable these measurements, a 1 mm GFRP telecom fiber with a length of 100 m is routed along the length of the piles, following four vertical lines (Figure 7). Similar to the FBG and thermocouple sensors, the telecom fibers are embedded in a vertical groove and glued using epoxy glue of the type Araldite 2021-1.

3.2.2 Thermocouple sensors

The thermocouple sensors that have been previously discussed in Section 3.1.3 are also used during the lateral load tests to track the temperature distribution in the soil, which is then used for a temperature compensation of the distributed strain measurements discussed in Section 3.2.1.

3.3 Pore water pressure measurements

The pore water overpressures are measured in the direct vicinity of locations V1 and I1 (piles P1 and P2, respectively, see Figure 1), using dynamic strain gauge push-in piezometers of the type Geosense SGP-3501. At a distance of 1.5 m from the pile center (i.e. 0.5 m from the pile wall), three piezometers are located at a depth of 5 m, 10 m and 15 m below the surface. At a distance of 2.5 m from the pile center (i.e. 1.5 m from the pile wall), one additional piezometer is located at a depth of 5 m below the surface.

During the pile driving and decommissioning, the pressure measurements are performed at high speed by the data acquisition systems which also acquires the acceleration and temperature data (Section 3.1.4). The long-term evolution of the pore water pressures will also be monitored using a custom made Portenta-based data acquisition system.

4 CONCLUSIONS

This paper presents the pile installation and lateral load tests planned within the frame of the SAGE-SAND project, aiming to investigate the potential of vibratory driving as an alternative for impact driving for the installation of offshore monopile foundations. A full description of the test campaign, planned at the beginning of 2025, is provided. In addition, the paper provides an overview of the pile and site instrumentation, which has already been completed in the fall of 2024. The planned test campaign provides a unique opportunity, which, in combination with the laboratory experiments and the theoretical investigations within the frame of the SAGE-SAND project, is expected to lead to a detailed insight in the effect of soil ageing on the lateral behavior of monopile foundations installed by both impact and vibratory driving. The authors intend to make the dataset resulting from the experiments publicly available, such that it can serve as a bench-mark for further experimental and theoretical investigation.

AUTHOR CONTRIBUTION STATEMENT

K. Maes: Investigation, Methodology, Visualization, Writing-Original draft. **L. Simonin**: Methodology, Visualization. **C. Bayart**: Investigation, Methodology, Visualization. **A. Bertholet**: Investigation. **G. Anoyatis**, **H. Rattez**, and **S. François**: Supervision, Funding acquisition, Writing-Reviewing&Editing.

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