

Experimental investigation of the effects of installation method and soil ageing on the lateral response of hollow steel piles in Zeebrugge for the SAGE-SAND project

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ABSTRACT: This paper presents preliminary results from full-scale lateral load tests on 2 m-diameter hollow steel piles at a test site in Zeebrugge harbor, Belgium, as part of the SAGE-SAND (Soil Ageing around offshore wind turbine foundations - from operational response to decommissioning) project. After the presentation of the test set-up, the lateral response of piles is evaluated with respect to installation method and, separately, to six months of soil ageing in sand. One pile was installed using impact driving and one using vibratory driving, then they were tested against each-other immediately after installation. The same piles were then extracted and re-installed, and laterally tested after six months. Impact-driven piles consistently showed higher initial stiffness and greater lateral capacity than vibratory-driven piles. Ageing produced a modest stiffness increase for both methods over the serviceability displacement range, with negligible change in ultimate capacity. These trends suggest that early-life performance deficits from vibratory installation may not be compensated by soil ageing, though small-displacement stiffness can improve over time. The analysis here is limited to pile head load–displacement data from external sensors, providing a clear, comparable benchmark across conditions. Future work will exploit detailed fiber-optic strain and pore-pressure measurements to derive soil-pile interaction models. The results contribute rare large-scale field evidence on combined installation and ageing effects, supporting refinement of design guidance for offshore wind monopiles, particularly for vibratory-installed foundations.

KEYWORDS: offshore geotechnics, monopiles, vibratory installation, soil ageing, large-scale tests.

1 INTRODUCTION

The design of offshore wind turbine (OWT) monopile foundations relies critically on an accurate understanding of their lateral load–displacement behavior. Over the past decade, large-scale field tests have become a cornerstone for improving geotechnical models for laterally loaded piles, most notably the PISA project (McAdam *et al.*, 2019) and its follow-up PICASO project (Byrne *et al.*, 2025), which have delivered benchmark datasets and advanced design methodologies. These studies, along with other national and international research initiatives, have shown that medium- to large-scale in-situ testing can significantly reduce the uncertainties inherent in scaling from small laboratory or centrifuge tests to full-scale OWT conditions.

In parallel, the Cuxhaven “Vibro” project (Achmus *et al.*, 2020) provided novel large-scale data on the lateral performance of monopiles installed by impact driving and vibratory driving. That study indicated that vibratory driving can lead to lower initial lateral stiffness and capacity compared to impact driving, while also emphasizing that the chosen vibratory driving parameters strongly influence the subsequent pile behavior. These findings have raised important questions for offshore design practice, particularly regarding whether post-installation soil processes, such as ageing, can mitigate these differences over operational time scales.

Beyond installation method effects, time-dependent changes in sand, commonly referred to as ageing, can

significantly alter pile response. While most field evidence to date focuses on axial capacity gains in driven piles (e.g., Jardine *et al.*, 2006), the underlying mechanisms of creep, stress redistribution, and development of interparticle bonding at the pile–soil interface are also expected to influence lateral stiffness at service displacements. Recent work at the University of Western Australia (Bittar *et al.*, 2020; Bittar and Lehane, 2025) has provided detailed field evidence on ageing mechanisms, based on 52 tension tests on pipe piles in sand to evaluate the effects of installation method, pile diameter, steel type, and load history. Their results indicate substantial capacity increases over time and emphasize that installation mode and steel type both influence the rate and magnitude of ageing. However, targeted field evidence isolating lateral ageing effects in full-scale hollow steel monopiles remains scarce, providing strong motivation for the immediate versus six-month comparisons undertaken in this study.

The present work contributes to this growing body of evidence by reporting on the first phase of full-scale lateral load tests conducted at the SAGE-SAND test site in Zeebrugge, Belgium. Four instrumented steel monopiles with a diameter of 2 m and a length of 21 m were installed in predominantly sandy soils using either vibratory or impact driving. Lateral tests were performed both immediately after installation and after six months of ageing, allowing direct comparison of the influence of installation method and soil ageing on global lateral response.

This paper focuses on preliminary analysis of the global pile head behavior as recorded by external displacement sensors, without yet exploiting the detailed distributed fibre-optic measurements that will allow depth-resolved interpretation in later publications. The results provide a clear and directly comparable indication of differences between installation techniques and the modest influence of ageing on stiffness and capacity, serving as an initial benchmark for future, more detailed analyses.

2 EXPERIMENTAL SET-UP

The section summarizes information on the test site and the experimental set-up. More details can be found in the installation and lateral loading test set-up of Maes *et al.* (2025) and the geotechnical site overview of Nunzia *et al.* (2024).

2.1 Characteristics of the site

The experimental site is located in the Port of Antwerp-Bruges, Zeebrugge (Belgium), see Figure 1. It was selected because the local subsurface conditions closely mirror those typical of OWT parks in the Belgian North Sea.



Figure 1. Location of the test site in Zeebrugge harbour

The subsoil comprises up to ~22 m of Quaternary deposits over lighter Tertiary and Quaternary layers, underlain by deeper Tertiary formations; groundwater is saline.

Extensive geotechnical investigations were conducted to define soil stratigraphy and properties, including boreholes, cone penetration tests (CPTs), seismic CPTs, multichannel analysis of surface waves, cross-hole tests, and laboratory characterization.

CPT data were processed to delineate layered soil units and estimate engineering properties (e.g., strength, stiffness) following Belgian guidelines and empirical correlations as described by Nunzia *et al.* (2024).

2.2 Characteristics of the piles

Four instrumented steel monopiles (P1 to P4) were installed, each with an outer diameter of 2 m and a length of 21 m (Maes *et al.*, 2025). The present study focuses on piles P3 and P4 which have a very similar profile: wall thickness variation with depth is shown in Figure 2.

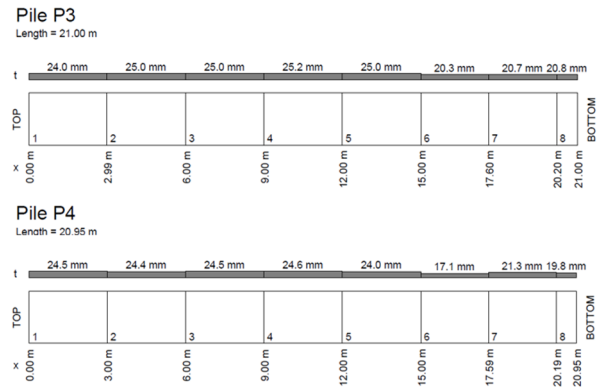


Figure 2. Pile wall thicknesses (t)

These two piles have first been installed (P3 vibratory driven, and P4 impact driven) with a 17 m embedment, laterally tested and extracted with the help of a vibratory hammer, then re-installed (this time P3 impact driven, and P4 vibratory driven) 15 m away from their initial positions in January 2025. Then they were laterally tested in June 2025.

The impact hammer used was a S-200 IQ Hydrohammer, while the vibratory hammer was a PVE 150M.

2.3 Tests set-up

The paired testing of P3 and P4 under identical subsurface conditions enables direct comparison of installation effects and ageing response.

Lateral load tests were performed using a custom reaction frame comprising two steel reaction units connected by rods, similar to the system described in Achmus *et al.* (2020). Hydraulic jacks applied lateral loads at the pile heads, measured by load cells, while displacement was monitored via wire-rope potentiometer sensors and a telemeter laser. This is pictured in Figure 3.

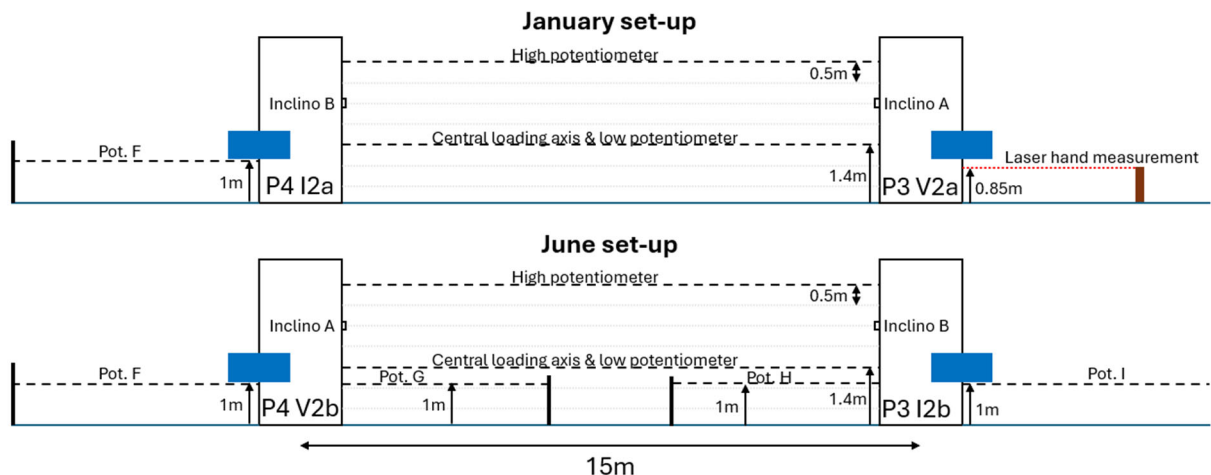


Figure 3. January and June tests set-up, including potentiometers (dashed black lines), telemeter (dotted red), and the loading half-crowns (in blue).

The displacement measurement set-up was improved from the January to the June tests:

- In both tests, two potentiometers linking the two piles were used as well as one inclinometer per pile, allowing to record the tilt of the piles and their relative displacement.
- In January, one exterior potentiometer (F) and one laser hand measurement were used to record the absolute displacement of the piles.
- In June, the laser hand measurement was abandoned, but three additional potentiometers (G-H-I) were used, as well as a motion capture device on one pile, in order to better characterize the ovalization of the piles, and thus be able to better interpret and integrate the results.

The testing protocol was a monotonic lateral loading up to 500 mm summed displacement at load height, with three unloading-reloading cycles to characterize the stiffness, as well as creep period to capture the quasi-static response of the tests.

2.4 Sensor equipment

A comprehensive sensor array was deployed to capture various aspects of pile–soil behavior (see Maes et al., 2025):

- Fiber Bragg Gratings: P3 and P4 were outfitted with vertical strings of FBG strain sensors (18 sensors per string, spaced every ~2 m), embedded in grooves and glued for deformation measurement during driving.
- Distributed Fiber-Optic Sensors: The piles had distributed telecom fiber (GFRP-coated) installed along four vertical lines, interrogated using Rayleigh backscatter via a LUNA interrogator, for real-time bending-strain profiles during lateral loading.
- Shock Accelerometers: Mounted near the pile top, these captured high-frequency accelerations during pile driving for pile driving analysis (PDA).
- Thermocouples: Embedded at various depths in pile P3 to record temperature changes during installation and loading.
- Pore-Pressure Sensors: Push-in strain-gauge piezometers were installed around piles at multiple depths (5 m, 10 m, 15 m, and at different radial distances) to monitor overpressures and liquefaction potential.
- Other measurements included video calendaring marks, and soil plug level measurements.

Although this paper focuses on global lateral response recorded by external displacement sensors, the acquired fiber-optic and pore-pressure datasets will enable depth-resolved analysis such as derivation of full p-y curves, assessment of bending moment distribution, ageing trends, and installation-method-specific behavior. These analyses will be reported in future publications as they require more elaborate processing.

3 LATERAL LOADING TEST RESULTS

The analysis presented here focuses on a comparison between the January (immediately post-installation) and June (six months post-installation) test campaigns. Only measurements from sensors that allow consistent comparison between the two campaigns are used: forces were recorded by the loading-rig load cells in both campaigns; June displacements were measured by potentiometers F and I, while January displacements were taken from potentiometer F and extrapolated from combined laser-hand measurements and inclinometer A. All displacements reported correspond to

points located one meter above ground surface on the external pile face, rather than at the neutral fiber, and should therefore be interpreted accordingly when comparing to design reference displacements.

3.1 Effect of the installation technique

Figure 4 and Figure 5 compare the load–displacement curves for the impact-driven and vibratory-driven piles in January and June, respectively. In both test series, impact-driven piles exhibit a consistently stiffer initial response and higher capacity across the displacement range. At the serviceability-to-ultimate transition ($\approx 0.1 D$ displacement at mudline), the impact-driven piles achieve 10–20 % greater lateral capacity than their vibratory-driven counterparts. This corroborates findings by Achmus et al. (2020).

The unloading-reloading loops, which can only be compared in June, are also stiffer and present less energy dissipation for impact driven piles.

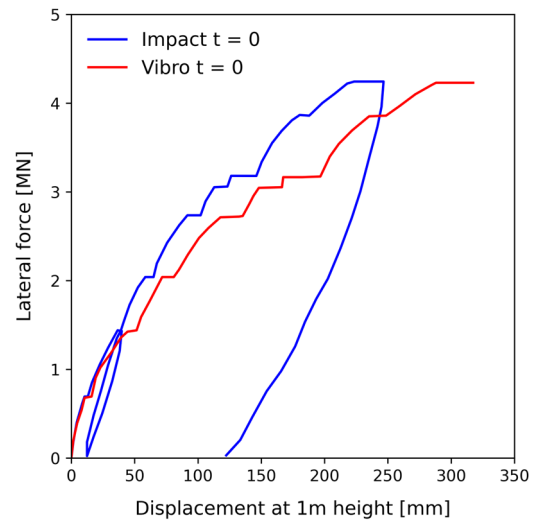


Figure 4. Lateral loading test immediately following installation.

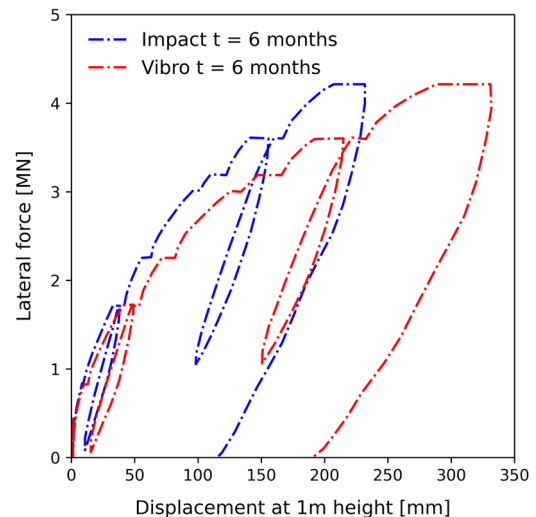


Figure 5. Lateral loading test six months after installation.

3.2 Effect of ageing

Figure 6 and Figure 7 compare the January and June results for the same installation techniques, isolating the effect of six months' ageing in the surrounding sand. Both installation types exhibit a modest but consistent increase in initial stiffness over the serviceability displacement range. This gain is likely linked to time-dependent mechanisms in sand, such as stress

relaxation, particle rearrangement, and cementation effects at the pile–soil interface, as reported in ageing studies by Bittar et al. (2020) and Bittar & Lehane (2025).

However, ultimate lateral capacity appears essentially unchanged over this ageing period. This indicates that the stiffness gains are most relevant at small to moderate displacements. This could root from the larger soil mass involved in failure mechanisms at large deformation which includes zones unaffected by soil ageing.

Tests after one year of installation will also be conducted.

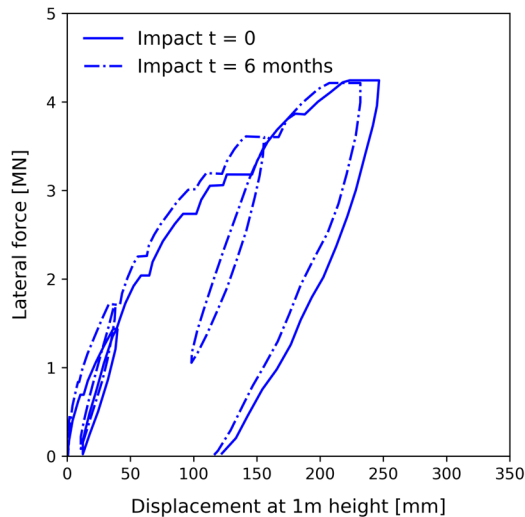


Figure 6. Lateral loading results for impact driven piles.

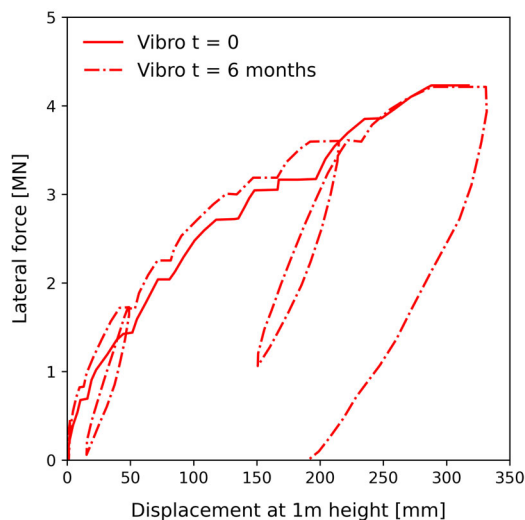


Figure 7. Lateral loading results for vibratory driven piles.

4 CONCLUSION AND PERSPECTIVES

A preliminary analysis of full-scale lateral load tests on 2 m diameter steel monopiles installed at the SAGE-SAND test site has been presented. The comparison between vibratory and impact driving in sandy ground indicates that vibratory installation leads to a clear reduction in both lateral stiffness and ultimate capacity, with a reduction in capacity of close to 20 %. Ageing over six months produced a modest increase in stiffness for both installation methods but had little influence on ultimate capacity.

The tests reported here were intentionally limited to global pile head measurements obtained from external displacement sensors, providing a straightforward and comparable dataset across installation methods and ageing periods. A much richer

dataset is available from the instrumented piles, including distributed fiber-optic strain measurements and pore pressure records, which will allow depth-resolved analysis of soil-pile interaction and the derivation of p–y curves in future work.

These results offer rare large-scale field evidence on the combined effects of installation method and ageing on the lateral response of monopiles in sand. The data provide an important benchmark for ongoing development of design models for vibratory-installed offshore monopiles and highlight the need to consider potential stiffness deficits in early-life conditions. Further analysis within the SAGE-SAND project will examine long-term ageing trends on the same test site, and the influence of installation parameters, cyclic loading and chemical effects in small-scale experiments and numerical studies, with the aim of refining industry guidance for the design of next-generation offshore wind foundations.

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