Document Version
Final published version

Citation (APA)
Peccin da Silva, A., Post, M., Elkadi, A. S. K., Kementzetzidis, E., & Pisanò, F. (2023). Effect of installation parameters and initial soil density on the lateral response of vibratory-driven monopiles: a laboratory study. In *Offshore Site Investigation Geotechnics 9th International Conference Proceeding* (pp. 1838-1846). (Offshore Site Investigation and Geotechnics). Society for Underwater Technology. https://doi.org/10.3723/LFBS1210

doi:10.3723/LFBS1210

Effect of installation parameters and initial soil density on the lateral response of vibratory-driven monopiles: a laboratory study

A. Peccin da Silva, M. Post & A.S.K. Elkadi
Deltares, Delft, The Netherlands

E. Kementzetzidis & F. Pisanò
Delft University of Technology, Delft, The Netherlands

ABSTRACT: The vibratory installation of monopiles as foundation for offshore wind turbines is considered a plausible solution next to the conventional installation method (impact-hammering). One of the main advantages is the lower noise emissions, reducing harm to the marine life. However, knowledge on the effects of the vibratory installation parameters on the lateral response of monopiles – and how these effects differ from those caused by impact-driving – is limited. This paper presents the results from an ongoing Joint Industry Project (SIMOX) with focus on 1g laboratory tests carried out in a 9.0m x 5.5m x 2.5m tank with saturated sand at Deltares, the Netherlands. The tests involve the installation (impact and vibratory) of scaled piles with 32 cm diameter, embedment length of 1.5 m and two wall thicknesses. The lateral loading regime consisted of monotonic and cyclic lateral loading. The results show the effect of soil density and different installation parameters of vibratory installation on the lateral response of the piles compared to a conventional impact installation.

1 Introduction

Monopiles are currently the predominant type of foundations for offshore wind turbines in the North Sea and worldwide. The current installation method consists of hydraulic pile driving by means of impact hammering the tubular steel piles into the seabed. However, the increasing size of monopiles has led to problems associated with the conventional installation method, notably high underwater noise (Tsouvalas, 2020). In that context, the use of vibratory installation has been investigated over the last years as a plausible low noise installation method.

These offshore foundations differ from typical piles used onshore in the sense that they are subjected to horizontal cyclic loads induced by the repeated action of waves and wind on the top structure, hence the design is usually governed by lateral stiffness. Previous research based on field (e.g. Achmus et al., 2020) and laboratory (e.g. Labenski et al., 2019; Hoffmann et al., 2020; Spill et al., 2020) tests have indicated a softer lateral behaviour for vibratory-driven piles in comparison with impact-driven piles in dense sand. On the other hand, Anusic et al. (2019) and Kementzetzidis et al. (2023) showed from field tests that, in medium-dense sand, vibro-piles behaved stiffer than impact-driven piles.

However, the knowledge on the effect of installation settings of the vibratory hammer on the lateral stiffness is still limited. Achmus et al. (2020) showed from large-scale field tests in dense sand (pile diameter of 4.3 m and a length-to-embedment depth ratio (L/D) of approximately 4.3) that the one pile installed with low frequency of the vibro-hammer (15 Hz) exhibited stiffer behaviour than the two piles installed with higher frequency (22.5 Hz) – though still slightly lower than the stiffness observed for the impact-driven piles. Nevertheless, definitive conclusions cannot be drawn due to the limited number of tests carried out in that study, as well as the fact that not only the frequency but also the installation procedure (i.e. number of interruptions during driving) differed from the other vibrated piles.

In other studies that varied the installation parameters (Labenski et al., 2019; Hoffmann et al., 2020; Labenski, 2020), it was suggested that an important aspect that governs the lateral response of piles is whether the vibration mode is “cavitational” or “non-cavitational”. A non-cavitational vibration mode occurs when the pile tip is always in contact with the adjacent soil whereas a cavitational mode occurs when the pile tip loses contact with the soil during the upward displacement stage within a vibration cycle. These studies suggested that a non-cavitational installation leads to a low lateral stiffness whereas a cavitational installation leads to a stiffer lateral response, which is more similar to – though still slightly lower than – the stiffness of impact-driven piles. However, determining whether the vibration mode is (non-)cavitational is not trivial. Rodger & Littlejohn (1980) associated cavitational or non-cavitational vibration modes with slow or fast vibratory driving, respectively, whereas Vogelsang (2016) related a cavitational or non-cavitational mode to large or small displacement amplitude of the pile tip during vibro-installation. Overall, determining the vibration mode is challenging as there are not direct ways of measuring it.

In terms of cyclic loading, few studies have analysed the effect of pile installation on the cyclic behaviour of laterally-loaded monopiles. Hoffmann et al. (2020) showed from scaled model tests that the accumulated lateral displacements converge for impact-driven and vibrated piles. Kementzetzidis et al. (2023) showed from scaled field tests onshore that the lateral stiffness of piles installed with three different installation methods (impact, axial vibro, and the GDP technique, which combines torsional and axial vibro), although initially different, later converged for all piles after a cyclic loading programme that involved small-amplitude ‘dynamic’ loading stages interleaved with medium-amplitude cyclic loading.

In addition to the valuable insights provided by the previous studies, there is need for a larger dataset of tests with broader range of installation parameters, e.g. frequency of the vibro-hammer, lowering speed and crane (hook) load. In that regard, the current paper presents the results from a scaled lab testing study, which is part of a larger research program (Joint Industry Project: SIMOX), at 1g conditions in which the effect of installation parameters on the lateral behaviour of scaled piles is analysed for vibro and impact-hammered installed piles. The Water-Soil Flume laboratory tests, which were finalised in October 2022, are a stepping stone towards larger scale onshore testing planned for later in 2023. The results from the scaled lab tests show the influence of sand density, installation method and parameters on lateral displacement under monotonic and cyclic loading.

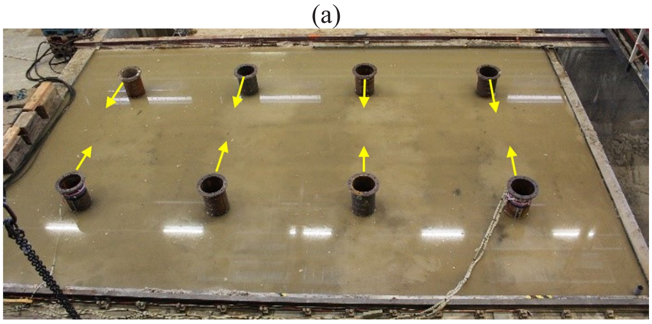
2 Experimental set-up

2.1 *Testing facility, preparation and measurements*

The tests were conducted in the Water-Soil Flume at Deltares, Delft, the Netherlands, which consists of a tank with 9.0 m of length, 5.5 m of width and 2.5 m of depth, with a multipurpose wagon on rails above the tank (Figure 1a). The tank was filled with saturated sand up to a height of 2.4 m in compacted layers of approximately 50 cm. The compaction took place using vibrating needles attached to the wagon, as shown in Figure 1a. For each layer, the compaction consisted of 3 runs of needles along the tank extension, with each run approximately 15-20 cm higher than the previous one, so that 3 runs were needed to compact every 50 cm.

The experimental programme consisted of four batches. Representative CPT profiles for batches 1, 2 and 3 with dense sand (target relative density 70% to 90%) and for batch 4 with medium-dense sand (target relative density 40% to 60%) are shown in Figure 2. Results from batches 2, 3 and 4 are presented in this paper. For each of these batches, 8 piles were installed (Figure 1b) and subsequently subjected to horizontal loading. The centre-to-centre distance between piles was 8D in the loading direction and 6.5D perpendicular to the loading direction. The distance between the piles and walls of the tank was 4.3D. Piles were loaded in the direction indicated by yellow arrows in Figure 1b such that boundary effects were minimised. The distance from the pile tip to the bottom of the tank was 2.8D. All distances were larger than the minimum distances recommended by Tasan et al. (2011). CPTs before pile installation and after pile loading, 1D from each other, at mid-distance between pile pairs (i.e. 4D from each pile), showed negligible differences in cone resistance. Pore pressure transducers were attached to the walls of the tank to verify potential liquefaction due to pore pressure build-up effects during pile installation and cyclic loading, which was found to be negligible in all stages.

(a)



(b)

Figure 1. Water-Soil Flume at Deltares: (a) vibrating needles for soil compaction; (b) top view with 8 piles installed in the tank.

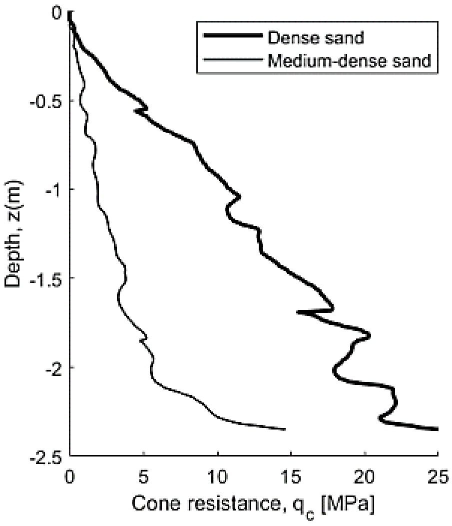
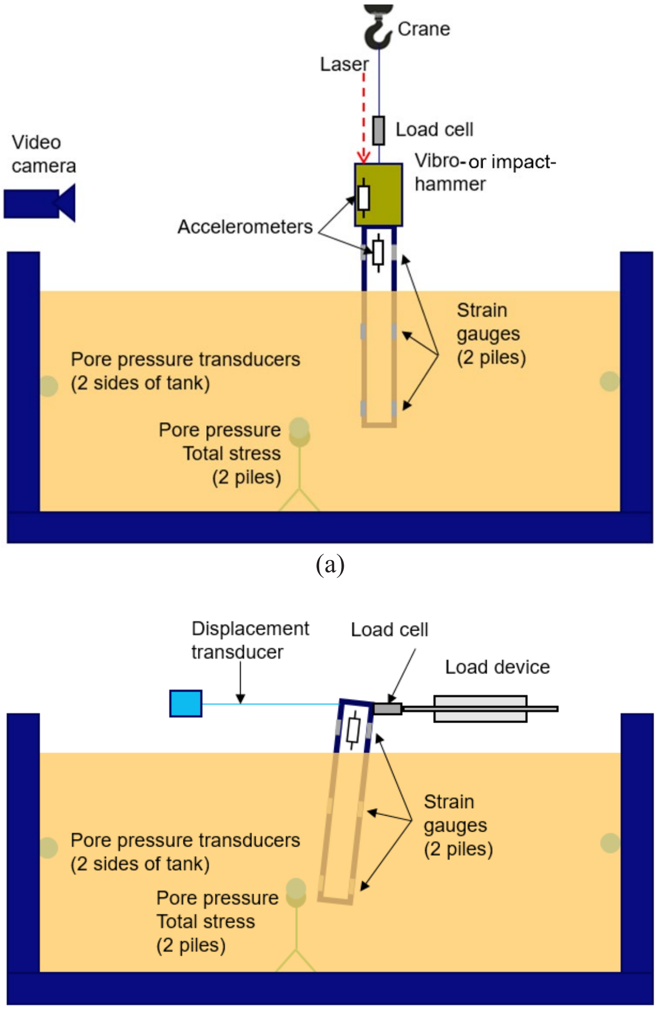


Figure 2. Representative CPT profiles for medium-dense and dense batches.

The model set-up is illustrated in Figure 3. Accelerations were measured during vibratory pile installation, with triaxial accelerometers both on the vibro-hammer and on the pile head, and the blow count was recorded during impact-driven installation. The vertical pile motion was measured by a high-accuracy laser sensor. The hook load was measured by a load cell placed between the lower end of the crane and the vibro-hammer (Figure 4), which was connected to the pile by means of a bolted interface plate. The soil was instrumented at two pile positions with total stress sensors and pore pressure sensors near the pile tip at approximately 1D in the horizontal direction from the pile centre. An increase in pore pressure during vibro installation was observed for all piles installed at the instrumented positions. The excess pore pressures quickly dissipated at the end of installation. The observed increase in pore pressure during impact installation was found to be less significant or even negligible. During lateral loading, horizontal force and displacement were measured at the pile head, as well as total stress and pore pressure in the soil next to the pile tip. The force was measured by a load cell between the actuator and the load application point, whereas the displacement was measured with a magnetostrictive linear position sensor (Figure 5).



(a)

(b)

Figure 3. Lab set-up for (a) pile (vibro) installation; (b) loading.

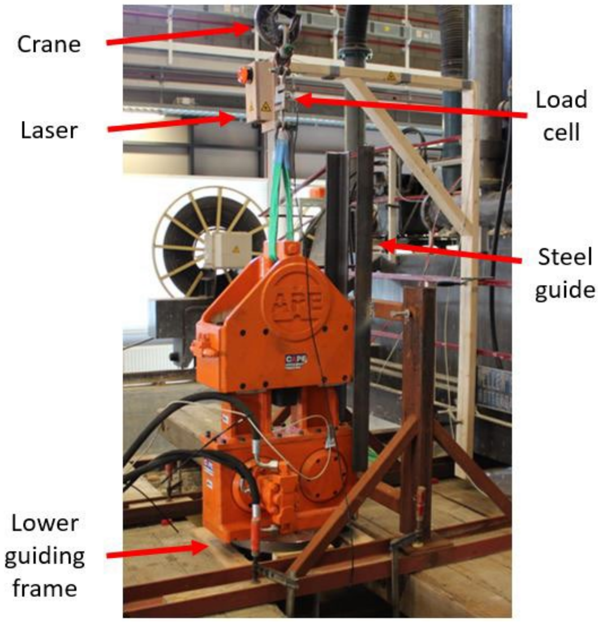


Figure 4. Set-up used for pile installation

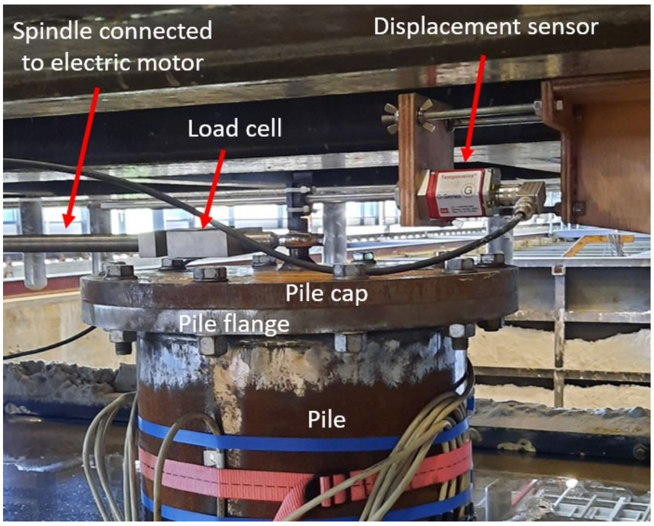


Figure 5. Lateral force and displacement devices

2.2 *Soil characteristics*

The scaled model tests were conducted with saturated Sibelco S90 sand (Balder et al., 2020; Coronel et al., 2020), which is a medium-fine sand with high sphericity and sub-angular shape. The sand has a mean particle size of d_{50} = 0.147 mm and a coefficient of uniformity c_u = 1.6, and average maximum and minimum densities of 1.590 and 1.333 g/cm^3, respectively.

2.3 *Pile properties*

Steel piles with outer diameter D = 0.32 m and total length of L_p = 2.0 m were used for the tests. Six piles had a wall thickness t = 4 mm (D/t = 81) and two piles had t = 10 mm (D/t = 32). The embedded length was L = 1.5 m, hence the L/D ratio was 4.6, which is considered representative for offshore monopiles. The piles had an external flange at the top for multiple purposes e.g. attachment of the vibro-hammer and connection of lateral loading and displacement devices.

2.4 *Installation equipment*

An impact hammer and a vibro hammer were used for pile installation. The impact hammer used was a HL750 dropping weight piling machine. For the installations in dense sand, a falling weight of 285 kg with a drop height of 0.4 m was used, whereas for the piles in medium-dense sand the dropping height was 0.1 m. The hydraulic vibro-hammer used was a model APE-23, with an eccentric moment modified from the standard 2.3 kg.m to a lower value of 1.3 kg.m. The vibro-hammer was connected to an overhead crane (see Figure 4), which had two possible lowering speeds during installation: 10 mm/s (low speed) or 110 mm/s (fast speed).

Two guiding systems were used during pile installation (shown in Figure 4): a metal frame attached to dragline mats (that were supported by the edges of the tank) was used to prevent rotation of the vibro-hammer as well as tilting in one direction. In addition, a second guiding system was placed in between the dragline mats, as indicated in Figure 4.

2.5 *Lateral loading device*

Lateral loading was applied by an in-house built lateral loading device consisting of an electric motor connected to a spindle as shown in Figure 5. The loading device was connected to the wagon above the tank. The wagon movement during lateral loading was measured by an independent system and was found to be negligible.

2.6 *Testing programme*

The testing programme, which was conducted between June and October 2022, consisted of 8 lateral loading tests per batch, with a total of 24 lateral loading tests, of which 16 piles were installed with vibration (11 in dense sand, 5 in medium-dense sand) and 8 with impact hammering (5 in dense sand, 3 in medium-dense sand). A selected number of piles in dense and medium-dense sand is presented in this paper to illustrate some of the findings from the Water-Soil Flume testing programme.

Each pile was loaded in three stages: (i) an initial monotonic stage from zero to 0.25 H_{ult}, where lateral bearing capacity H_{ult} is defined as the load at which the pile exhibits a displacement of 0.1D at ground level – obtained from 3D FE analyses in dense and medium dense sand; (ii) purely one-way cyclic loading (1000 cycles for most piles, but 100 or 500 cycles for some piles) from zero to 0.25 H_{ult} with a cyclic frequency of 0.1 Hz; (iii) a final monotonic stage up to the maximum load supported by the system. The load level for the cyclic loading was selected based on typical values for monopiles, based on previous studies (e.g. Hoffmann et al., 2020; Kementzetzidis et al., 2023). The lateral bearing capacity H_{ult} was estimated prior to the tests by means of a 3D finite-element model (FEM), which will not be detailed in this paper for the sake of brevity.

The installation settings used for each pile are presented in Table 1, where the nomenclature stands for the batch number followed by the pile number and the installation method (e.g. B2-P1v stands for batch 2, pile 1, vibratory installation).

Table 1. Test programme: selected representative tests.

Pile ID*	t (mm)	Method	Vibro		Cycles
			Frequency	Speed	
B2-P3i	10	Impact	-	-	100
B2-P8v	10	Vibro	High	Low	100
B3-P1v	4	Vibro	High	Free	1000
B3-P3i	10	Impact	-	-	1000
B3-P4v	4	Vibro	Medium	Free	1000
B3-P5v	4	Vibro	Low	Low	1000
B3-P6v	4	Vibro	High	Low	1000
B3-P7i	4	Impact	-	-	1000
B3-P8v	10	Vibro	Low	Free	1000
B4-P1v	4	Vibro	Medium	Low	1000
B4-P2v	4	Vibro	Medium	High	1000
B4-P4v	4	Vibro	Medium	High	1000
B4-P5v	4	Vibro	Medium	Low	1000
B4-P6i	4	Impact	-	-	1000
B4-P7i	4	Impact	-	-	1000

* B2 and B3 = dense sand; B4 = medium dense sand

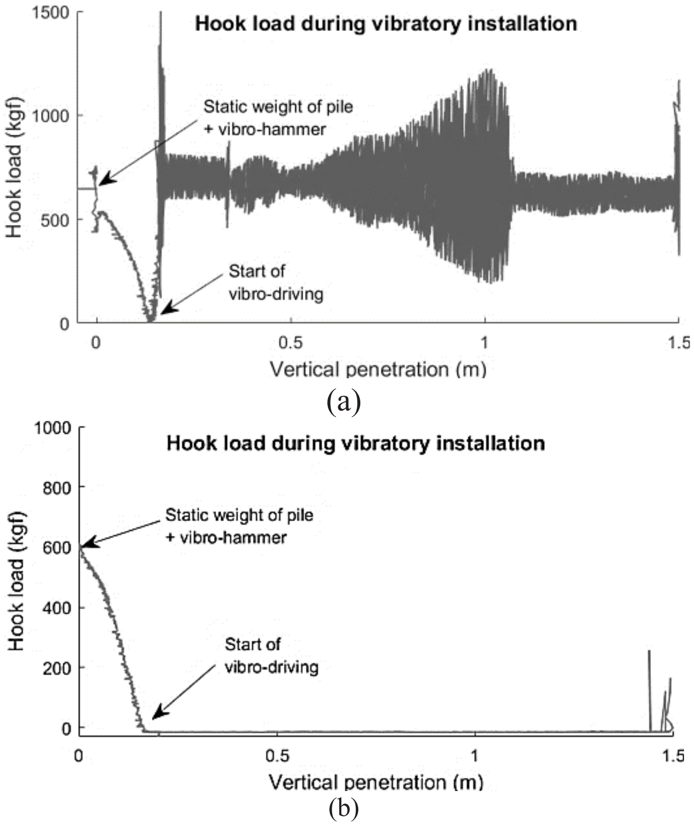
3 **Results and discussion**

The results are divided into dense and medium-dense sand, for installation and lateral loading.

3.1 *Dense sand: installation and initial monotonic loading*

As shown in Table 1, different installation parameters were tested as part of the experimental programme. The different combinations of lowering speeds of the crane (low, high) with the different frequencies of the vibro-hammer (low, medium, high) led to different types of vibratory installation: crane controlled or free hanging. During crane-controlled installation, the weight of the whole pile-hammer system was sustained by the overhead crane, hence the hook load measured by the load cell oscillated around the self-weight of the pile-hammer system. For some cases, the weight was taken partially by the crane and partially by the soil. Figure 6 presents the hook load as a function of the vertical penetration for two piles: Pile B3-P6v in Figure 6(a) is an example of a fully crane controlled installation, whereas Pile B3-P4v in Figure 6(b) is a representative example of a fully free hanging installation (i.e. hook load equals zero).

For the crane-controlled pile installations, both the lowering speed of the crane + hammer + pile system and the frequency of the vibro-hammer varied, as shown previously in Table 1.



(a)

(b)

Figure 6. Different modes of vibratory installation: (a) crane-controlled; (b) free-hanging.

The initial monotonic force-displacement curves of selected thin-walled piles in dense sand are shown in Figure 7. It can be observed that the lateral displacement at 0.25 H_{ult} for the impact-driven pile is just slightly smaller than that for the crane-controlled vibrated piles (i.e. the impact-driven pile is slightly stiffer than the crane-controlled vibrated piles, if the secant stiffness is considered at 0.25 H_{ult}). An additional observation is that the frequency of the vibro-hammer seems to have little influence on the lateral response of crane-controlled vibrated piles, as both piles B3-P5v and B3-P6v (vibrated with high and low frequency, respectively) exhibit similar lateral stiffness.

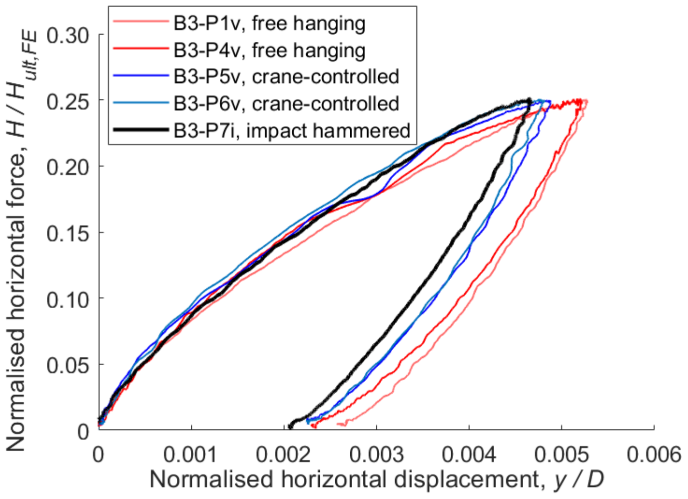


Figure 7. Load-displacement curves for initial monotonic load for impact-driven and vibrated thin-walled piles in dense sand.

On the other hand, for both piles installed with free-hanging vibration, the lateral displacement at 0.25H_{ult} is somewhat larger in comparison with impact-driven and crane-controlled vibrated piles. As for the crane-controlled piles, the lateral stiffness of the two free hanging piles seems to be little influenced by the vibration frequency, as the force-displacement curves for B3-P1v and B3-P4v (vibrated with high and medium frequency, respectively) are similar.

The observation that the vibration frequency seems to have little influence on the lateral stiffness differs from the conclusions of Achmus et al. (2020). In that study, the authors observed that the pile installed with low vibration frequency and penetration speed behaved stiffer than those with higher frequency and penetration speed, which suggested that a higher frequency and penetration speed generated installation effects that led to a lower lateral stiffness. However, the load taken by the crane was not measured in the tests of Achmus et al. (2020), hence the differences in lateral stiffness might have occurred due to different installation modes (free hanging and crane-controlled). Another possible explanation is that the difference in scales may cause different installation effects – scaling effects will be addressed in the upcoming large-scale field tests in SIMOX. The reader is also referred to section 3.4for a discussion on the (dis)advantages of 1g testing in comparison to full-scale testing or centrifuge testing.

The difference between the lateral stiffness of free hanging and crane-controlled vibrated piles is even more pronounced for thick-walled piles (D/t = 32), as shown in Figure 8. The results are presented separately for batches 2 (Figure 8a) and 3 (Figure 8b) as they are not directly comparable due to slight differences in soil density (though in both batches the sand was dense). It is shown that the pile installed with crane-controlled vibration behaves more similarly to the impact-driven pile in comparison with the pile installed with free hanging vibration, which exhibits a much softer lateral behaviour in comparison with the respective impact-driven pile in the same batch.

These observations on the effect of free hanging or crane-controlled installation on the lateral response of piles can be related to the findings of Labenski et al. (2019), Labenski (2020) and Hoffmann et al (2020) on the effect of cavitational and non-cavitational modes of vibratory installation on lateral stiffness. Piles installed with crane-controlled vibration in the current study exhibit similar behaviour to impact-driven piles, which is also the case for piles installed by cavitational mode of vibration in the aforementioned literature. This suggests that a crane-controlled installation leads to a cavitational vibration mode. It is reasonable to assume that, if the pile is 'held back' by the crane during vibratory installation, a gap between pile tip and the adjacent soil may be created, leading to a cavitational installation. On the other hand, if the pile is free hanging, i.e. if its weight is totally supported by the soil, the pile tip is more likely to remain in contact with the underlying soil, which characterises a non-cavitational vibration mode.

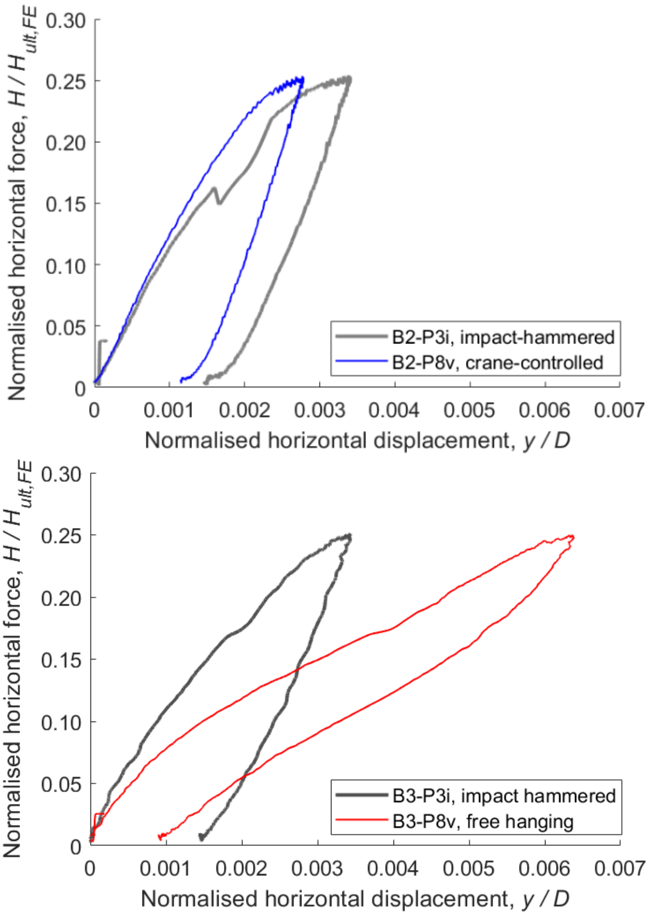


Figure 8. Load-displacement curves for initial monotonic load for impact-driven and vibrated thick-walled piles in dense sand: (a) batch 2; (b) batch 3.

The softer behaviour observed for piles installed with free hanging vibration could be attributed to various reasons, such as the difference in pore pressure effects and the difficulty in controlling the pile verticality during installation. For all free hanging piles, inclination was observed approximately halfway through installation, which was corrected in the final part of installation. The exact inclination during installation was not measured, which will be done in the onshore field tests.

3.2 *Dense sand: cyclic loading*

After the initial monotonic loading stage, all piles were subjected to cyclic loading, as previously shown in Table 1. The cyclic loading stage led to changes in lateral stiffness due to changes in the soil state.

The lateral secant stiffness (at 0.25 H_{ult} load level) observed during cyclic loading normalised by the stiffness in the first cycle is shown in Figure 9, where K_N is the lateral stiffness after N cycles and K_{ini} is the initial stiffness for the first loading cycle (i.e. loading stage (ii), after the initial monotonic loading of stage (i) – see section 2.6). It is shown that, although the stiffness in the monotonic stage is larger for the impact-driven pile (as shown previously in Figure 7), the gain in lateral stiffness is less pronounced for this pile. For the vibrated piles, on the other hand, the gain in stiffness during cyclic loading is larger. In fact, the piles that had lower lateral stiffness in the initial monotonic stage had a larger increase in lateral stiffness during cyclic loading. For instance, while for the impact-driven pile (B3-P7i) the gain in lateral stiffness after 1000 cycles in comparison with stiffness at the first loading cycle of stage (ii) was approximately 16% (i.e. $K_N/K_{ini} = 1.16$), for the free hanging vibrated piles the increase after 1000 cycles was up to 54% ($K_N/K_{ini} = 1.54$ for B3-P1v). However, it shall be noted that despite the larger increase in lateral stiffness for vibro-installed piles, the impact-driven pile still exhibited the stiffest lateral response among all piles after 1000 cycles. Another observation from Figure 9 is that the increase in lateral stiffness decreases with increasing number of cycles and becomes very small after 1000 cycles, which suggests that the increase in lateral stiffness of the piles seems to stabilise in the long term.

The observations of lateral stiffness suggest that the differences in the initial effects of pile installation on lateral behaviour can reduce with cyclic loading, which is in line with the findings of Hoffmann et al. (2020), Kementzetzidis (2023) and Kementzetzidis et al. (2023). However, Hoffmann et al. (2020) suggested that the lateral displacement of piles installed by impact and vibro installation converge to a single value after 1000 cycles. This observation was not confirmed during the lab tests and will be further investigated in the onshore field-testing campaign. Kementzetzidis (2023), on the other hand, observed that after 5000 cycles the difference in lateral stiffness of piles installed with different methods decreased to a seemingly steady value, although this stiffness value was not the same for all piles. The findings of Kementzetzidis (2023) are in line with those reported in the current paper.

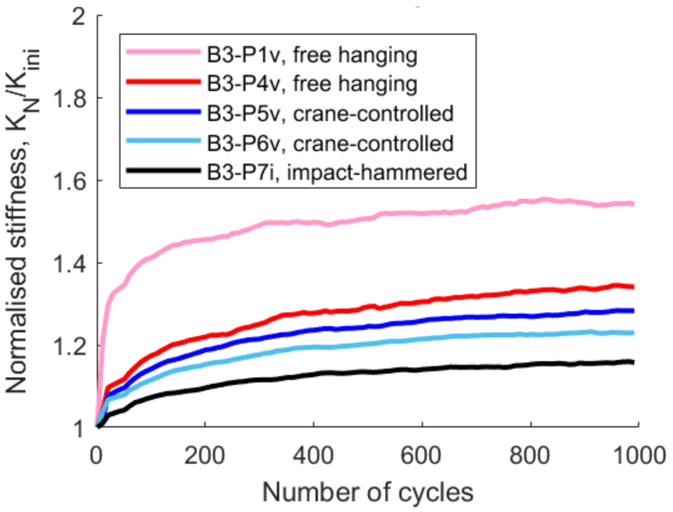


Figure 9. Lateral stiffness with the number of cycles, normalised by the initial stiffness for the 1st loading cycle.

3.3 *Medium-dense sand: installation and initial monotonic loading*

The piles in medium-dense sand were initially loaded up to 0.25 H_{ult}. It is worth noting that, due to the lower density of the sand in batch 4 in comparison with the previous batches, H_{ult} was lower than the value obtained for the dense sand batches. Since only one batch was prepared with medium-dense sand, the frequency of the vibro-hammer was kept constant for all (vibro) installations, as well as the installation mode, which was crane-controlled for all piles. The only parameter that was varied was the penetration speed: two out of four vibrated piles were installed with high penetration speed and two other piles were installed with low penetration speed. In addition to the four vibro-installed piles, two piles were driven into the soil by impact hammering.

The force-displacement results of the initial monotonic tests for thin-walled piles installed in medium-dense sand are shown in Figure 10. It can be seen that the two piles vibrated with high lowering speed behaved distinctly softer than those vibrated with low lowering speed. The impact-driven piles exhibited horizontal displacement that was either similar or smaller (i.e. stiffer lateral response) than the low-speed vibrated piles, and significantly smaller than the displacement of both high-speed vibrated piles. Previous field test results presented by Anusic et al. (2019) for piles with D = 16.5 cm and embedded length L = 4 m (i.e. L/D = 24) in medium-dense sand showed that the vibrated piles exhibited larger lateral stiffness under monotonic loading than the impact-driven piles. Both vibrated piles were installed with the same frequency and same penetration speed, hence the influence of installation speed observed in the current paper was not analysed by Anusic et al. (2019). The stiffer behaviour observed in those tests was attributed by Anusic et al. (2019) to soil compaction during vibratory installation. Therefore, the stiffer behaviour of the low-speed (vibro) piles may be attributed to the larger number of vibration cycles imposed to the soil by low-speed installation as a consequence of the longer duration of the pile installation. In fact, CPTs carried out before and after pile installation show a significant increase in qc values and hence suggest an increase in soil density. These observations will be verified during large-scale onshore field tests which will involve a larger number of pile tests.

Besides the possible influence of soil densification, the larger lateral stiffness observed for low-speed installation may be related to a cavitational installation mode, as shown by Labenski et al. (2019). In that study, the pile installed in medium-dense sand with cavitational mode exhibited stiffer lateral behaviour than the pile installed with non-cavitational mode. The cavitational pile installation in Labenski et al. (2019) was slower than the non-cavitational one.

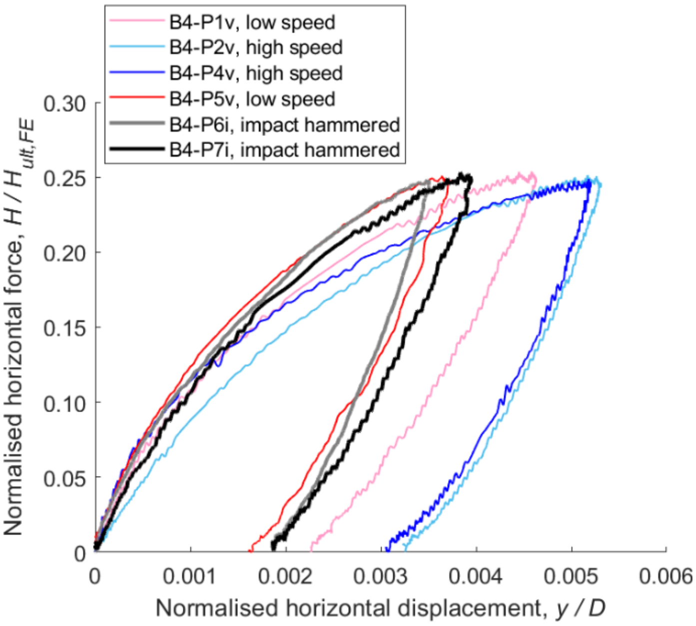


Figure 10. Load-displacement curves for initial monotonic load for impact-hammered and vibrated thin-walled piles in medium-dense sand.

Therefore, the apparent relationship between low and high lowering speed with cavitational and non-cavitational installation, respectively, is worth further analysis and research.

In addition to the results of Anusic et al. (2019) and Labenski et al. (2019), the field tests reported in Kementzetzidis et al. (2023) also showed that piles with D = 76 cm and embedded length L = 8 m installed in medium-dense sand with vibratory techniques behaved stiffer than impact-driven piles.

3.4 *Scaling effects*

It is acknowledged that the lower soil stress levels in the current 1g study in comparison with full-scale offshore conditions could influence both strength and stiffness. However, the use of centrifuge testing (in which stress levels are more comparable to those in full-scale) would bring its own disadvantages and challenges, such as interpretation of results of scaled installation tools.

The 1g testing set-up as presented in this paper, although with lower stress levels, has provided a valuable contribution to the SIMOX project. Firstly, by generating qualitative insights in the relevant trends and effects of vibro installation compared to impact installation. These insights will be used as input to prepare for the scheduled onshore tests in SIMOX. Secondly, by allowing to gain quantitative insights in scaling effects when combined with the upcoming results of the onshore tests.

4 **Conclusions and next steps**

A testing programme was conducted in the Water-Soil Flume laboratory at Deltares to analyse the effect of installation method and parameters on the lateral behaviour of monopiles by means of scaled tests.

The results suggest that the behaviour under initial monotonic loading is affected by the installation method. In dense sands, piles installed with the conventional method of impact driving behaved stiffer than those installed with vibration. For the vibrated piles, the lateral stiffness seems to be affected by the hook load during installation, i.e. whether the installation is free hanging (i.e. zero hook load) or crane-controlled (i.e. hook load oscillating around the static weight of the system). Free hanging piles exhibited a softer behaviour whereas crane-controlled piles behaved stiffer than the free hanging vibro-piles and just slightly softer than the impact-driven piles. This could be related to the pile loss of verticality during free hanging installation, which was observed visually but not measured – this will be measured during the onshore field tests to be carried out later in 2023. The difference between free hanging and crane-controlled piles was even more pronounced for thick-walled piles. The frequency and the speed of vibratory installation (for crane-controlled installation) did not have a large influence on the lateral response of the piles installed in dense sand.

On the other hand, for the piles installed in medium-dense sand, where the installation of all vibrated piles was crane-controlled, the lowering speed during vibratory installation seems to have a significant effect. Piles installed with low speed exhibited lateral response similar or marginally softer than impact-driven piles, whereas piles installed with high speed showed distinctly softer lateral behaviour compared to all other piles.

From the piles installed in dense sand and subsequently subjected to cyclic loading, the differences between different installation methods seem to decrease. The gain in lateral stiffness during cyclic loading for the (initially softer) free hanging piles with respect to the initial stiffness in the first cycle was higher than the gain for the impact driven (initially stiffer) piles, especially in the first 100 cycles, which suggests that the differences in the initial effects of pile installation on lateral behaviour may reduce with cyclic loading.

Although the results provide insights on the effect of installation on lateral behaviour of monopiles, the results cannot be directly extrapolated to larger scales. In that regard, the results presented in the current paper are a first step towards the SIMOX large-scale field tests, which will also provide information on the scaling effects.

The results and learnings from the Water-Soil Flume laboratory testing will be used as input for the large-scale onshore field-testing programme that will be carried out later in 2023. The onshore tests will involve the installation and lateral loading (monotonic and cyclic) of monopiles with 2.2 m diameter. The scope will be extended in relation to the tests presented in the current paper, and a total of 4 installation methods will be analysed: impact (as the reference case), axial vibro, torsional vibro combined with axial vibro (i.e. Gentle Driving of Piles – GDP), and water jetting combined with axial vibro (Vibrojet).

5 Acknowledgements

This paper is part of the SIMOX joint industry project in the framework of the GROW Research Programme. The project is funded by Topsector Energiesubsidie from the Dutch Ministerie van Economische Zaken en Klimaat, grant number MOOI12001, and financial/technical support from the following partners, in alphabetical order: Boskalis, CAPE Holland, Deltares, Delft Offshore Turbine (DOT), Delft University of Technology, GBM Works, Heerema Engineering Solutions, Heerema Marine Contractors, IQIP, Ocean Winds, Ørsted, RWE, Seaway7, Shell, Siemens Gamesa Renewable Energy, Sif Netherlands, TNO, TotalEnergies, Van Oord, Vattenfall.

The contribution to the tests of, in alphabetical order, Bastiaan van der Veen, Brice Dijksman, Cedrik de Roo, Danko Boonstra, Jaap Elstgeest, Kees van Beek and Marcel Busink, is also appreciated.

References

Achmus M, Schmoor KA, Herwig V and Matlock B. (2020). Lateral bearing behaviour of vibro- and impact-driven large-diameter piles in dense sand. Geotechnik, 43(3): 147-159.

Anusic I, Lehane BM, Eiksund GR and Lingaard MA. (2019). Influence of installation method on static lateral response of displacement piles in sand. Géotechnique Letters, 9, 193-197.

Balder T, De Lange D, Elkadi ASK, Egberts PJP, Beuckelaers WJAP, Coronel M, van Dijk J, Atkinson R and Luger HJ. (2020). Hydraulic pile extraction scale tests (HyPE-ST): experimental design & preliminary results. In: 4th International Symposium on Frontiers in Offshore Geotechnics, ISFOG 2020, 746–756.

Coronel M, Elkadi ASK, Slot H, Hendriks C. (2020). Hydraulic pile extraction scale tests for testing the removal of piles from the soil at the end of their operational life, Public report.

Hoffmann B, Labenski J and Moormann C. (2020). Effects of Vibratory Driving of Monopiles on Soil Conditions and Their Cyclic Lateral Load Bearing Behavior. In: 4th International Symposium on Frontiers in Offshore Geotechnics, ISFOG 2020, 714–724.

Kementzetzidis, E. (2023). Cyclic behaviour of laterally loaded (mono)piles in sand. PhD Thesis, TU Delft, The Netherlands.

Kementzetzidis E, Pisano F, Elkadi ASK, Tsouvalas A and Metrikine AV. (2023). Gentle Driving of Piles (GDP) at a sandy site combining axial and torsional vibrations: Part II – cyclic/dynamic lateral loading tests. Ocean Engineering, 270, 113452.

Labenski J and Moormann C. (2019). Lateral bearing behaviour of vibratory-driven monopiles: A modified p-y approach based on experimental observations of scaled model tests. In: 17th European Conference on Soil Mechanics and

Geotechnical Engineering, ECSMGE 2019 – Proceedings, 1867-1874.

Labenski J. (2020). Untersuchungen zum Einbringverhalten und dem lateralen Tragverhalten unter monotoner Einwirkung von in nichtbindigen Böden vibrierend installierter Monopiles. PhD Thesis, Institute for Geotechnical Engineering, Univerity of Stuttgart, Germany.

Rodger AA and Littlejohn GS. (1980). A study of vibratory driving in granular soils. Géotechnique 30(3): 269–293.

Spill S, Foglia A and Dührkop J. (2020). Comparison of p-y methods with large-scale tests of impact- and vibratory-driven piles. In: 4th International Symposium on Frontiers in Offshore Geotechnics, ISFOG 2020, 1302-1311.

Taşan HE, Rackwitz F and Savidis S. (2011). Experimentelle Untersuchungen zum Verhalten von zyklisch horizontal belasteten Monopiles. Bautechnik 88(2011) Heft 2, DOI: 10.1002/bate.201110010.

Tsouvalas, A. (2020). Underwater Noise Emission Due to Offshore Pile Installation: A Review. Energies 13(12): 3037.

Vogelsang J. (2016). Untersuchungen zu den Mechanismen der Pfahlrammung. Dissertation, Veröffentlichungen des Instituts für Bodenmechanik und Felsmechanik, Heft 182, Karlsruher Institut für Technologie, Karlsruhe.