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Influence of hook load on vibro-driven pile installation in sand

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ABSTRACT: Vibro-driving is increasingly being considered as an installation method for monopiles of offshore wind turbines. It is a dynamic installation method with lower acoustic emissions than the traditional impact driving, and vibro-driving has been reported to result in rapid yet controlled pile installation in sand. The risk of pile run is mitigated as the pile is clamped to the vibro-driver, which is connected to the crane. Besides cyclic degradation (friction fatigue) and tip reversal, dynamic effects and, in saturated conditions, excess pore pressures are important. Pile installation is performed with the applied dynamic force resulting from the product of the vibration frequency, the eccentric counter-rotating masses and their eccentricity. Pile mass and (parts of) the vibro-driver contribute to the static force. The interplay between these inputs and vibro-driven pile response is complex and non-unique. This contribution focuses on the influence of the crane tension or hook load on the vibro-driving outcome. The hook load reduces the static force but not the dynamic mass and becomes particularly important near refusal. Available physical data from vibro-driven pile installations in sand at different scales (small scale tests performed in the centrifuge and medium scale tests performed in a test pit) are drawn on. results from postdiction modelling are presented before the effect of hook load is explored.

Keywords: Vibro-driving; monopile; sand; pile installation; hook load

1 INTRODUCTION

The vast majority of bottom-fixed offshore wind turbines are supported by monopiles. Traditionally, these have been installed by impact-driving, but as monopiles continue to grow in size to keep up with ever increasing size turbines, alternatives are being considered. Larger piles require larger impact hammers delivering more energy to the system to drive the pile into the seabed. This introduces technical and practical challenges, and also goes hand in hand with increased acoustic emissions. Regulations on acoustic emissions vary regionally, but often result in mitigation measures being required to maintain noise levels from impact-driven monopile installations below allowable limits.

Vibro-driving is an alternative pile installation method whereby vertical vibrations are applied to the pile. This vertical dynamic force F_{dyn} is generated by eccentric pairs of masses that counter-rotate (giving the eccentric moment M_e (in kgm) and cancelling out non-vertical forces) at a selected angular rotation velocity ω which is linked to the frequency f through Eqn. 1 such that the vertical dynamic force amplitude can be calculated with Newton's law ($F = ma$) as:

$$\omega = 2\pi f \tag{1}$$

$$F_{dyn} = M_e \omega^2 \sin \omega t \tag{2}$$

The vibro-driver is connected to the crane of the installation vessel and clamped to the pile, such that it can be used as an up-ending tool as well and mitigates the risk of pile run. The displacement amplitude of the vibro-driver (in air) s_0 relates to

$$s_o = \frac{M_e}{m_{dyn}} \tag{3}$$

where m_{dyn} refers to the dynamically excited part of the vibro-driver. During pile installation, the vibro-driver needs to vibrate the mass of the pile as well, which increases the dynamic mass m_{dyn} (now consisting of the mass of the pile and the dynamically excited part of the vibro-driver plus clamping system) and hence reduces the displacement amplitude. The soil resistance (and in case of longer piles, elasticity) further influences the actual displacement amplitude during pile driving.

The static driving force resulting from the self-weight of the system can be written as

$$F_o = (m_{dyn} + m_{sup})g - F_{hook} \quad (4)$$

where m_{sup} is the mass of the suppressor housing that is the top part of the vibro-driver which de-couples the vibrations being applied to the pile from the crane, and g is Earth's gravity. The crane may hold back some of the self-weight by applying crane tension or hook load F_{hook} to control pile when the force delivered by the vibro-driver can easily overcome the driving resistance. This can be related to soft soil conditions or a powerful hammer or a combination of both. The hook load changes the applied static force, but not the mass or the dynamic force and frequency. This has been shown to significantly change the radial effective stresses around the installed pile and has also been commented to affect the post-installation lateral response (e.g. Labenski, 2020; Stein 2023; Peccin da Silva et al. 2023).

This paper focuses on the influence of hook load on vibro-driven pipe pile installation in sand. A database of physical vibro-driven pile installation results was used to evaluate postdictions before the same numerical approach was used to illustrate the influence of hook load on the expected pile response.

2 DATA BASE

The database comprises measurements from independently performed vibro-driven pile installations at different scales and in different sands: small scale model tests performed in the centrifuge (Bienen et al. 2023, Mazutti 2024) and medium scale tests in a test pit (Stein 2023).

2.1 Centrifuge tests

The centrifuge tests included here were performed on a 3D printed rough steel model pile with a diameter D = 50 mm and wall thickness t = 0.5 mm at 20g (hence representing a prototype pile of 1 m diameter) in water saturated medium dense UWA silica sand (with a relative density D_r = 68%) to an embedded length $L \approx 4D$.

The mini vibro-driver (Figure 1) is a bespoke design for the centrifuge. Its working principle is based on vertical vibration of a single mass: a motor, on top of the device, drives a belt and pulley system which rotates an undulated wheel; the undulations drive a slider up and down, generating the vertical vibrations. A rod, on top of the device, which slides through a linear rail (connected to the actuator), ensures vertical pile installation. Zero hook load is applied. More details can be found in Mazutti et al. (2024).

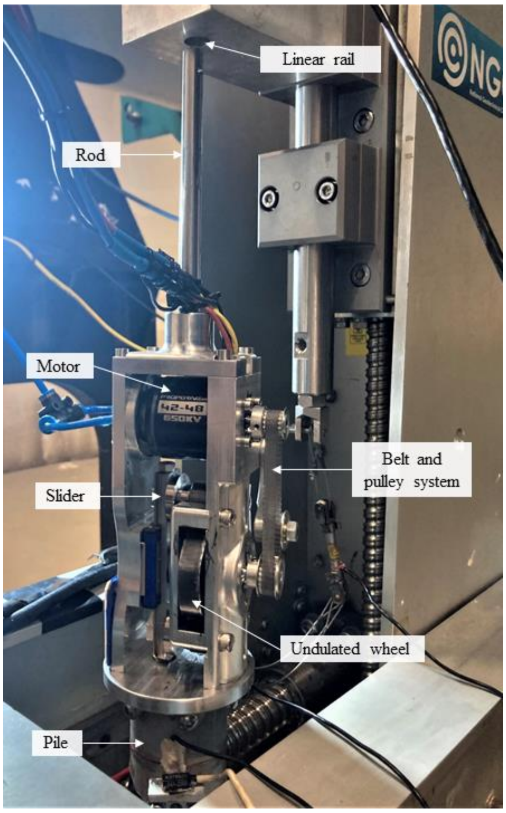

Figure 1. Mini vibro-driver for centrifuge testing (Mazutti et al. 2024)

2.2 Medium scale tests

Medium scale tests (Figure 2) were carried out in geotechnical testing pits with a model pile consisting of a stainless steel tube with a diameter D = 0.6 m, wall thickness t = 3 mm and an embedment length L = 2.4 m. That model pile shall represent a typical offshore monopile of about 8 m diameter.

The medium scale test piles were installed in water saturated dense Braunschweig sand with CPT values of 25 MPa at pile toe level. For the installation, a hydraulic vibratory driver type APE model 23 with an eccentric moment M_e = 2.33 and 1.36 kg·m respectively, was used. More details can be found in Stein (2023, 2024).

Two different modes of vibratory installation were used: In case of 'crane-guided' vibratory driving, the driving frequency was set to a fixed value that was sufficient to drive the model pile to target depth. The penetration speed was controlled by the crane. This resulted in a hook load $F_{hook} > 0$ which was measured with a load cell.

In case of 'free' vibratory driving, the pile-vibro assembly was not attached to the crane. The driving frequency was increased manually to achieve a certain penetration progress. The actual penetration speed is - in that case - a response parameter of the system. The hook load was $F_{hook} = 0$.

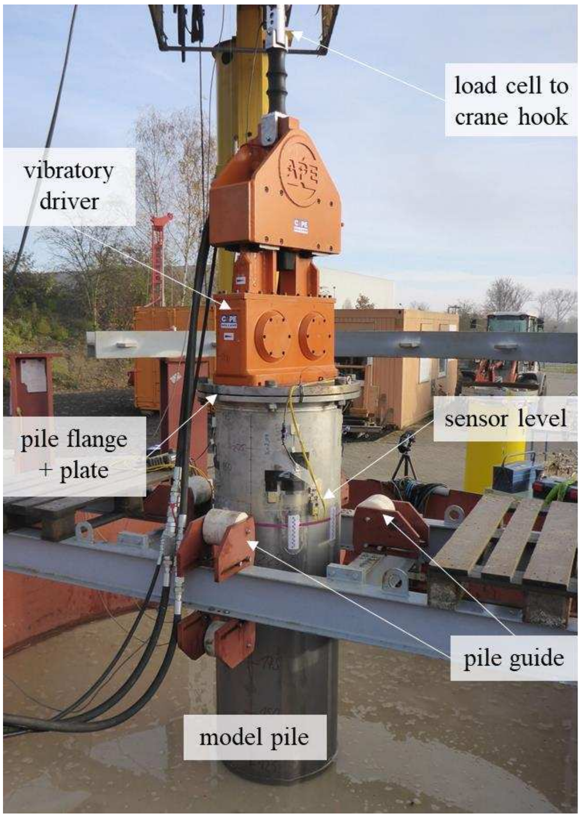

Figure 2. Test setup of medium scale tests (Stein, 2024)

2.3 Summary of test details

Relevant details of the database of vibro-driven pile installations in sand are summarised in Table 1, with information for the centrifuge tests "C-" provided in terms of prototype values for the centrifuge tests, the medium scale tests are denoted "M-".

In the medium scale model tests, the installations with varying frequency f (M-Z07, M-Z14) were carried out 'free' ($F_{hook} = 0$) while the installations with varying static force F_0 (M-Z11, M-Z15) were carried out 'crane-guided ($F_{hook} > 0$). More information on the medium scale tests and pile installation records can be found in Stein (2023).

Table 1. Vibro-installation details of the database.

Dataset	f (Hz)	F_o (kN)	M_e (kgm)	F_{dyn} (kN)
C-Test 1	21.7	137.2	17.16	318.4
C-Test 3	16.9	137.2	17.16	194.5
M-Z07	13 .. 26	9.7	2.33	16 .. 63
M-Z11	34	2.5 .. 3.2	1.36	62
M-Z14	14 .. 31	9.7	1.36	11 .. 51
M-Z15	26	3.5 .. 4.8	2.33	60

3 MODELLING METHODOLOGY

The postdiction modelling of the various pile vibro driving tests was conducted using AllWave-VDP (Allnamics, 2024). "VDP" stands for Vibro Driving Prediction, and AllWave-VDP is a wave equation program that utilizes the method of characteristics to simulate one-dimensional stress waves in the pile. This program enables simulation of the pile installation process through pile-soil interaction, employing multiple soil models, including those from Jonker (1987), Smith (1960), and Randolph and Simons (1986). Key parameters for calculating the driving force applied at the pile top include static surcharge (F_0), eccentric moment (M_e), driving frequency (f), vertical dynamic force (F_{dyn}, amplitude denoted as $\widehat{F_v}$), dynamic mass (m_{dyn}), free-hanging displacement amplitude (s_0). The driving capacity is the theoretical driving force (F_d) comprised of static and vertical dynamic forces (Equations 1-5), as shown in Figure 3.

$$F_d = F_0 + F_{dyn} \tag{5}$$

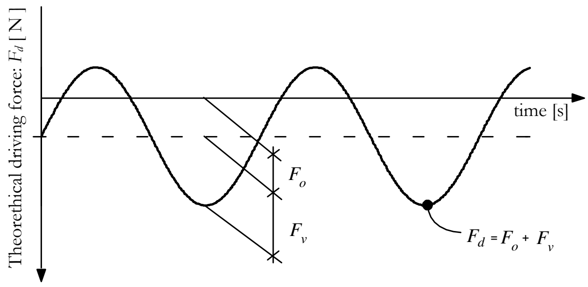

Figure 3. Influence of hook load on predicted pile refusal

The application of a hook load (F_{hook}) primarily affects the calculated penetration speeds, with a smaller impact on force, acceleration, velocity, and displacement amplitude during installation. Higher hook loads generally reduce the displacement and velocity amplitudes of the pile in the penetration direction, as more of the pile's weight is supported by the hook rather than engaging with the soil. This reduction can restrict the pile's penetration capacity, particularly in dense soil layers where larger amplitudes are often necessary to achieve effective advancement.

4 POSTDICTION RESULTS

This section serves to validate the approach and provide confidence in the results with varying hook load discussed in the following section. To this end, postdictions obtained using VDP are compared with the experimental results in the following sub-sections.

4.1 Postdiction of centrifuge tests

The centrifuge tests were modelled in terms of their equivalent prototype (Table 1), assuming the vibro-driver to be rigidly connected to the pile as it is bolted on top of the pile in the model (Figure 1). The frequency applied in tests C-Test 1 and C-Test 3 were used as input, because in the centrifuge tests it takes a couple of seconds for the full target frequency to be reached. Applying the target frequency from the outset in the VDP postdictions led to clear disagreement in the results.

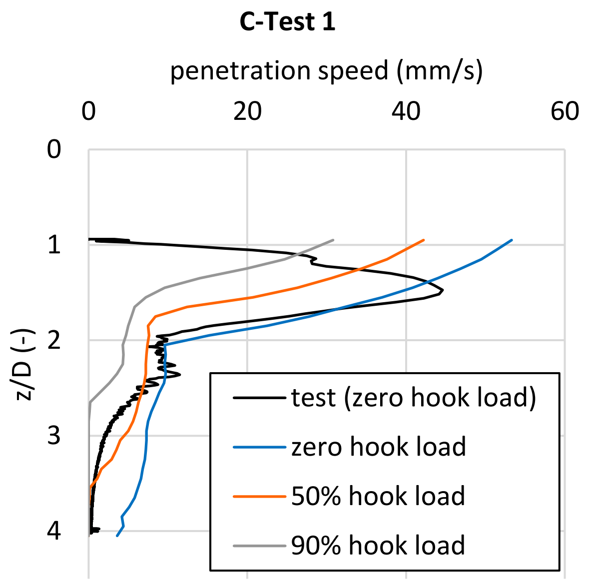

Figure 4. Average pile penetration speed, comparison between centrifuge test C-Test 1, VDP postdiction and hook load variation

The results of centrifuge test C-Test 1 are compared in Figure 4 with the VDP postdiction in terms of average pile penetration speed. From a self-weight penetration of approximately z = 0.9D, vibro-driving commenced, with initial rapid penetration that slowed progressively as expected as penetration resistance increased. The high and rapidly decreasing penetration speed from approximately z = 1.5D is captured well, including the sharp change in gradient at approximately z = 2.0D. While C-Test 1 and C-Test 3 were overall similar, the results of C-Test 3 do not feature the changes in gradient between 2.0 and 2.5D, hence the comparison with C-Test 1 is shown. From approximately z = 2.5D, however, the postdiction overestimates the average penetration speed.

The acceleration range, which VDP can predict separately at different levels, e.g. where the accelerometer is mounted in the centrifuge model at approximately 1D below the pile head (level 1) and at the pile toe which could not be instrumented in the model tests, shows significant oscillations but on average agrees well with the measurements. Figure 5 highlights the differences in the postdicted velocity range at level 1 compared to the pile toe. The VDP results fall either side of the measured velocity range between z = 2.0D and 2.5D, which is why the average penetration speed matches well at this penetration level but is higher thereafter.

For the postdictions, the Young's modulus E = 160 GPa was assumed as deduced for the 3D printed steel model piles. However, this value has an uncertainty range, and the choice of input value affects the VDP predictions.

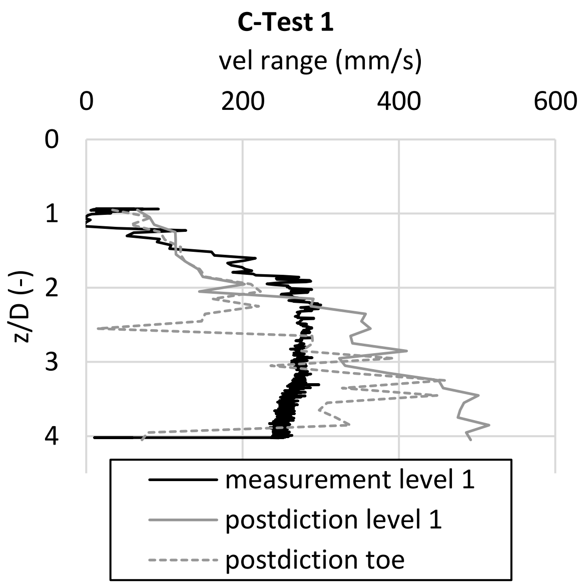

Figure 5. Velocity range, comparison between centrifuge test C-Test 1 and VDP postdiction

4.2 Postdiction of medium scale tests

The medium scale tests were modelled in terms of the actual model pile and vibro-driver (see Section 2.2). The soil model was set up based on the CPT results from the test pit. Some adjustments were necessary to model the pile flange and the plate which carried the vibro-driver (see Figure 2). Here, the actual masses were used but the geometry at the pile head was adjusted.

For all postdictions of the medium scale model tests, the driving frequency and hook load measured in the tests were used as input. Thus, for the 'free' vibratory driven piles no external load except for the self-weight of the pile and vibro was applied. For the 'crane-guided' vibratory driven piles, the hook load measured in the tests was applied to the system.

Results of tests and postdictions are compared at the pile level were strains and accelerations were measured in the tests, i.e. 0.5 m below the pile head.

Figure 6 shows the measured (black) and simulated (grey) velocity ranges over pile penetration from 'free' vibratory driven pile M-Z14 (left) and 'crane-guided' vibratory driven piles M-Z11 (right). Measurements and postdictions show a reasonable agreement. Especially for the 'free' vibratory driven pile, the increase and decrease of velocity range at the start and end of the installation process was met by the postdictions. The drop of velocity range at about 2.2*D* penetration is the result of an interruption of the pile installation necessary to open the pile guide (see Figure 2). The simulation results of the 'crane-guided' test show some fluctuations in the velocity signal that were not witnessed in the tests.

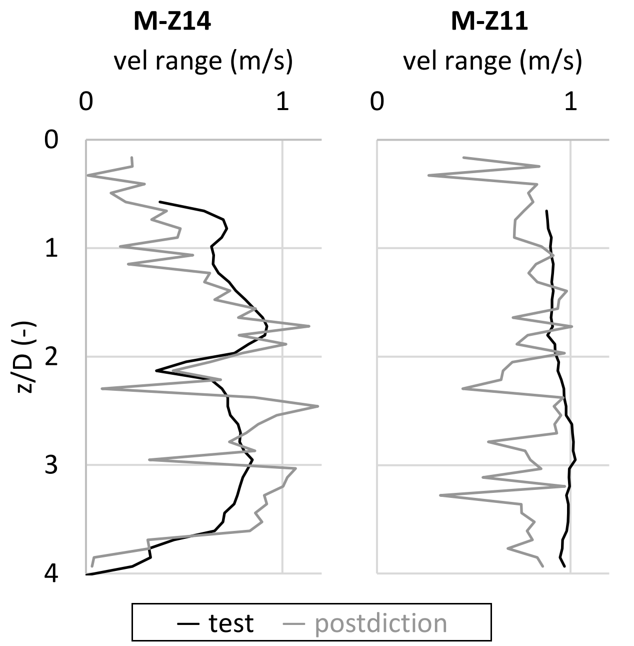

Figure 6: Velocity range, comparison between medium scale model tests and VDP postdictions

5 EFFECT OF HOOK LOAD VARIATION

Since the approach has been demonstrated to reasonably reflect the measured data, this section explores the effect of changes in the hook load on the predicted pile installation behaviour. There is not a pair of physical vibro-driven pile results with different hook loads and otherwise identical conditions, hence this is investigated through variation of the VDP input: For 'free' pile installation with zero hook load, variations were simulated with a constant hook load of 50% and 90% of the static weight of pile and vibro-driver, respectively. For 'crane-guided' pile installations with non-zero hook load, variations were simulated with zero hook load.

The influence of the assumed hook load on the predicted pile refusal depth is significant as shown in Figure 4 for the conditions relevant to C-Test 1. The plot includes the centrifuge test results (black) and the VDP postdictions with varying hook load. This relation of increased hook load with earlier refusal is not surprising as it reflects the reduced (static) driving force.

However, the predicted displacement range of level 1 and the pile toe changes, as shown in Figure 7. The amplitude of cyclic displacement in particular at the pile toe has been acknowledged to be instrumental in facilitating pile vibro-driving in sand (e.g. Cudmani 2001, Vogelsang et al. 2017).

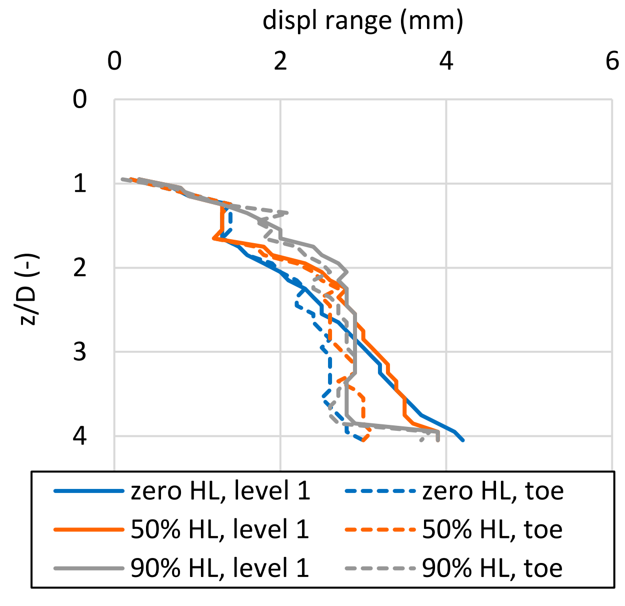

Figure 7. Influence of hook load on predicted pile refusal

For the medium scale model tests, Figure 8 shows the velocity ranges at the pile top from postdictions with varying hook load. Test M-Z14 was originally carried out by 'free' vibratory driving, thus with zero hook load. Additional simulations were carried out with constant hook loads of 50% and 90% of the self-weight of pile and vibro, respectively. Test M-Z11 was originally carried out by 'crane-guided' vibratory driving. The hook load was a response parameter of the system and varied over depth. An additional postdiction was carried out with zero hook load.

The courses of the velocity range over penetration depth do not show substantial changes due to a change of the hook load applied in the simulations. The same applies for other postdiction results such as displacement range and postdiction results at the pile toe.

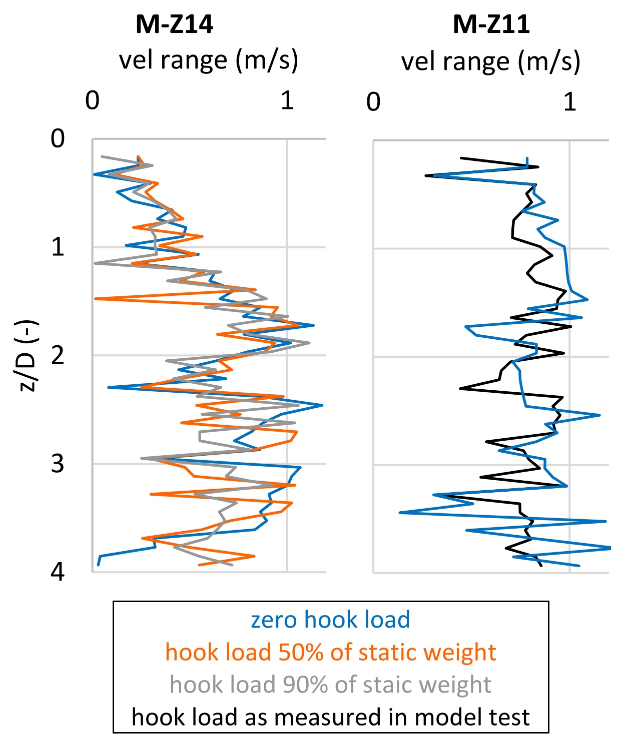

Figure 8: Influence of the hook load on the postdicted velocity range

6 CONCLUSIONS

In monopile vibro-installation offshore, the pile-vibro system is suspended by a crane which may hold back some of the system's self-weight. This reduces the static driving force without however changing the magnitude of the vibrated mass or applied dynamic force. The potential influence of such a hook load on the pile installation is explored here using a method that is widely employed in the industry. The results indicate that increased hook load can significantly influence the pile penetration speed and lead to earlier predicted refusal, but that the interaction is complex and requires further investigation.

AUTHOR CONTRIBUTION STATEMENT

B. Bienen: Conceptualization, Writing- Original draft. **P. Stein**: Investigation, Writing- Original draft. **R. Buitenhuis**: Methodology, Investigation, Writing-Original draft. **R. Van Dorp**: Writing- Reviewing and Editing, **K.Viking**: Writing- Reviewing and Editing.

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REFERENCES

Allnamics (2024). AllWave-VDP: Driveability software for vibratory driving.

Bienen, B., Mazutti, J.H., Bransby, M.F., Kazemi Esfeh, P., Randolph, M.F. (2023). Investigating installation and post-installation performance of vibro-driven monopiles in sand: centrifuge modelling and numerical analysis. *Proc. 9th Offshore Site Investigation and Geotechnics (OSIG 2023)*, London, UK, pp. 1830-1837.

Cudmani, R.O. (2001). *Statische, alternierende und dynamische Penetration in nichtbindigen Böden*. PhD Thesis, Karlsruhe University of Technology.

Jonker, G. (1987), Vibratory pile driving hammers for oil installation and soil improvement projects. Proc. 19th Offshore Technology Conf., Dallas, Texas, OTC 5422, pp. 549-560.

Mazutti, J.H. (2024). *Understanding vibratory pile installation in sand and its effects on pile response under lateral loading*. PhD Thesis, University of Western Australia.

Mazutti, J.H., Bienen, B., Bransby, M.F., Randolph, M.F., Wager, G. (2024) Development of a mini vibro-driver for pile testing in the centrifuge. *Int. J. Physical Modelling in Geotechnics*, , http://dx.doi.org/10.1680/jphmg.23.00056.

Labenski, J. (2020). *Untersuchungen zum Einbringverhalten und dem lateralen Tragverhalten unter monotoner Einwirkung von in nichtbindigen Böden vibrierend installierten Monopiles*. PhD Thesis, Stuttgart University, Germany.

Peccin da Silva, A., Post, M., Elkadi, A.S.K., Kementzetzidis, E. and Pisanò, F. (2023). Effect of installation parameters and initial soil density on the lateral response of vibratory-driven monopiles: a laboratory study. *Proc. 9th Offshore Site Investigation and Geotechnics (OSIG 2023)*, London, UK, pp. 1838-1846.

Randolph, M.F. and Simons H.A. (1986). An improved soil model for one dimensional pile driving analysis. Proc. 3rd International Conference on Numerical Methods in Offshore Piling, Nantes, pp. 3–17.

Smith, E.A.L. (1960). Pile driving analysis by the wave equation. *Journal of Soil Mechanics and Foundation Engineering (ASCE)*, Vol. 86, pp. 35-61 (Discussions in Vol. 87, SM1, pp. 63-75). Stein, P. (2023) *Stress state developments during the installation of pipe piles in sand and their influence on the lateral load-bearing behaviour.* Dissertation, Tech. Uni. Braunschweig, Germany. http://dx.doi.org/10.24355/dbbs.084-202301131107-0

Stein, P. (2024) Stress effects due to different installation methods for pipe piles in sand. *Geotechnical Engineering*, https://doi.org/10.1680/jgeen.23.00105

Vogelsang, J., Huber, G. and Triantafyllidis, T. (2017). Stress paths on displacement piles during monotonic and cyclic penetration. In *Holistic Simulation of Geotechnical Installation Processes*, Vol. 82, pp. 29–52.