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Influence of vibro-driver frequency on pile penetration in dry sand in a geotechnical centrifuge

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ABSTRACT: This article presents results of an experimental campaign on a scaled vibro-driver in sand conducted in TU Delft's geo-centrifuge as part of the GEOLAB funded project FoundEx. The aim of this experimental campaign is to explore the different parameters governing the vibro-driveability of a monopile within sand to improve the understanding of the phenomena at play, quantify the influence of driving parameters, and refine their selection to open new perspectives for the industry. After explaining the governing principles of vibro-drivers and the design of the miniature vibro-driver, the results of vibro-driving in dry dense sand under 50g for different vibrating frequencies are presented. These results are then analysed to quantify the relation between the vibratory frequency and the pile penetration, as well as its penetration rate.

Keywords: Offshore wind; Installation; Vibro-driving; Monopile.

1 INTRODUCTION

Monopiles are hollow steel cylinders. They are the prevalent foundation type (Wind Europe, 2020) for offshore wind turbines (OWT). As OWTs grow larger and are founded in deeper water, so do monopiles which typically now reach 10 m in diameter, 80 m length and close to 0.1 m wall thickness for a weight of over 2000 t. Until now, most monopiles have been driven into the seabed by impact hammering. However, this installation technique implies high energy impacts that cause large noise emissions, disturbing the marine fauna (Bailey *et al.*, 2010), and increase the monopile fatigue as well as risks of buckling. Furthermore, scaling-up of the hammers to match the growing monopiles is challenging. Alternative installation techniques are thus sought by the industry. Vibratory hammering, which has been used onshore for smaller foundations for decades (see Viking, 2002), is gaining traction within the industry. The potential benefits of vibratory hammering include significantly reducing the noise emission and the induced damage to the pile, being easily scalable through the juxtaposition of several hammers, avoiding the risks of pile run, and enabling quicker installation times (e.g., Bienen 2025). Nonetheless, vibratory driving is not yet routinely used for monopiles offshore because of a lack of confidence in driveability analyses and on its effect on the subsequent lateral behaviour of the OWT system. Noticeable early uses of the technology offshore are listed in Doherty *et al.* (2015), and CAPE Holland (2024) reports on the use of its hammers in the installation process of Moray West offshore wind farm.

Vibrodrivers have been developed since the 1930s, later focusing on the post-installation axial capacity from the 1960s (see Viking, 2002), and on the development of theoretical driveability models such as Rodger and Littlejohn (1980) or Holeyman *et al.* (1996). Research has also delved into the behaviour of vibrated sand (see Denies, 2010) to better understand the mechanisms behind the penetration of the vibrated foundation into the soil. Among studied foundation types, research on open-ended piles has only explored the driving of piles onshore which are considerably lighter and more slender than offshore monopiles. Research is now concerned with the driveability of lower embedment to diameter ratio of much larger piles and the focus is on post-installation lateral behaviour and its evolution over the lifecycle of an OWT. Early results of such research efforts can be found for medium scale field tests in sand on combined axial and torsional vibrations (Tsetas *et al.*, 2023) and for pure axial vibrations in the ongoing SAGE-SAND project (Letizia *et al.*, 2024), and at a smaller scale in the lab (Da Silva *et al.,* 2023; Fang *et al.*, 2024) or in the centrifuge (Mazutti *et al*., 2024).

The GEOLAB funded project FoundEx presented herein aims to understand better the vibratory driving process of monopiles. An experimental campaign in TU Delft's geo-centrifuge has explored the influence of different driving parameters, geometrical dimensions, and soil conditions on the penetration of a miniature monopile in sand. This study has taken advantage of the high stress levels in the soil provided by the centrifuge, the controlled environment and reproducibility of the tests, and its reduced dimensions to explore a large parametric space.

2 EXPERIMENTAL SET-UP

2.1 TU Delft's geo-centrifuge

The cylindrical container used for the experiments in dry sand was 295 mm in inner diameter and 190 mm in inner height. The height of the samples during tests was 160 mm. All experiments presented herein were conducted with a centrifuge acceleration field of 50g at one-third of the sample depth with an effective radius of 1.088 m.

2.2 Sample preparation

The samples were prepared with Geba sand. General properties of this fine-grained sand are presented in Table 1.

Table 1. Geba sand material properties

Parameter [Unit]	Symbol	Value
Median grain size [mm]	D_{50}	0.119
Coefficient of uniformity [-]	C_u	1.59
Max. void ratio [-]	e_{max}	1.07
Min. void ratio [-]	e_{min}	0.64
Specific gravity [-]	ρ_s	2.67
Critical state friction angle [-]	φ_c	31.7

All experiments presented herein were conducted on dry dense sand with relative density $D_r \approx 80\%$. Samples were prepared by dry pluviation in four layers, with intermediate shockwave compaction, and a final compaction on a vibrating table under an overburden pressure of 750 Pa.

2.3 Miniature vibro-driver

Vibratory hammers used in the field use pairs of counter rotating masses to create vertical vibrations. This principle was miniaturised and adapted to the use in a centrifuge. Figure 1 presents the miniature vibro-driver within the basket of TU Delft's geo-centrifuge.

The scaled prototype values are provided in square brackets in the following.

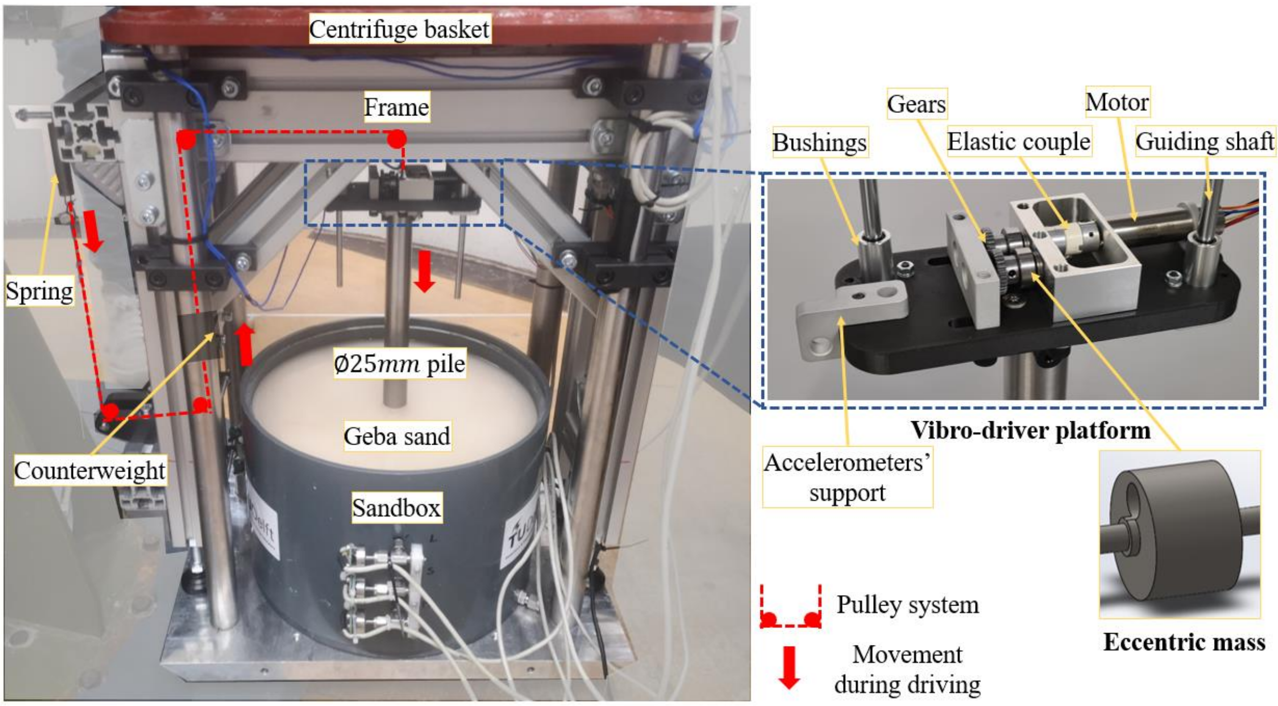

Figure 1 – Picture and schematic of the experimental set-up for a saturated experiment in TU Delft's geo-centrifuge.

The stainless-steel pile diameter was limited to D = 25 mm [1.25 m] to avoid lateral and bottom boundary effects. The thickness of the pile wall was 0.5 mm [25 mm], leading to a diameter-to-thickness ratio of 50, which is only slightly lower than common offshore practice, where the ratio ranges between 60 and 120. The vibrating frequency used in offshore practice is approximately 20 Hz, which corresponds to a 1 kHz standard frequency for the miniature vibro-hammer at 50g, following applicable scaling factors (e.g., Iai *et al*., 2005). The total eccentric moment used in this study is 4 g.mm [25 kg.m], which was scaled based on the selection in GRLWEAP (Pile Dynamics, 2024) of vibro-hammers capable of driving a corresponding prototype to a depth of 5D in dense dry sand. The eccentric masses and the motor were mounted on a platform rigidly attached to the pile. The platform comprises bushings which run along linear shafts to guarantee verticality during driving.

The pile and platform system masses were 60 g [7,500 kg] and 290 g [36,250 kg], respectively. A counterweight and a spring were used to reduce the static weight of the pile-platform system to 36 N [90 kN] during driving. The spring compensated for the movement of the pile-platform system and counterweight within the centrifuge acceleration field. The working principles of this miniature vibro-driver are further discussed in Simonin *et al.* (2024).

3 EXPERIMENTAL RESULTS

This study focused on the influence of the vibrating frequency on the driveability of this miniature pile for the standard eccentric moment $m_e = 4$ g.mm [25kg.m]. The amplitude of the vibrating force generated by a vibro-hammer is given by:

$$F_c = m_e \omega^2 \quad (1)$$

where $\omega = 2\pi f$ is the angular velocity and f is the vibrating frequency.

This study explored the penetration of the miniature pile for different frequencies resulting in different vibrating force amplitudes recorded in Table 2. The standard frequency of 1 kHz [20 Hz] results in the standard force $F_{c0} = 158$ N [395 kN].

The magnitude of the vibrating force should be compared to the static weight of 36 N [90 kN] and the dynamic weight of the platform-pile system subjected to vibration by the vibro-driver. At the target g-level of 50g, the dynamic weight evolves almost linearly with the movement of the system from 130 N [325 kN] at the sand surface, to 150 N [375 kN] at a penetration depth of 5D.

Table 2. Frequencies and resulting vibrating forces

Frequency in Hz	F_c	**Ratio to** F_{c0}
500 [10.0]	39.5 N [98.7 kN]	0.25
707 [14.1]	78.9 N [197 kN]	0.5
866 [17.3]	118 N [296 kN]	0.75
1000 [20.0]	158 N [395 kN]	1
1118 [22.4]	197 N [493 kN]	1.25
1225 [24.5]	237 N [592 kN]	1.5

Figure 2 presents the penetration depth normalised by the pile diameter over one minute [50 min] of driving under different vibrating frequencies. Time should be multiplied by 50 to extrapolate these results at the prototype scale. Time zero marks the start of the vibro-driving process, which occurred after the pile was allowed to settle under the static weight of the system and during the increase of g-level to the target of 50g. This initial settlement was equal to (0.26±0.03)D. While tests with frequencies of 1 kHz [20 Hz] or less could run for more than one minute, the motor controller could only maintain the rotational speeds of the tests at 1118 Hz [22.4 Hz] and 1225 Hz [24.5 Hz] for 40 s [33 min] and 11 s [9 min], respectively. This limitation was likely due to the increased friction of the mechanism occurring during driving at high frequencies. Although the vibro-driver continued to run at reduced frequencies, the corresponding driving is not displayed here for consistency.

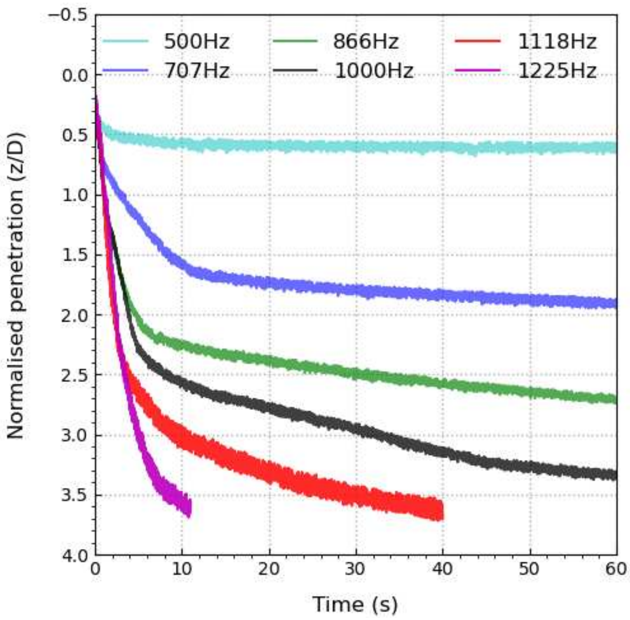

Figure 2 – Normalised penetration as a function of time for different vibrating frequencies.

Figure 2 demonstrates that the higher the vibrating frequency, and thus the higher the vibrating force amplitude, the deeper the pile penetrates. Figure 3 displays the penetration rate along the normalised penetration depth for the different frequencies tested. The penetration speeds in this figure are valid at prototype scale, as their scaling factor is unity. This figure is obtained with a mean smoothing of the progressive penetration of the pile over 0.5 s [25 s]. While the initial acceleration is comparable across different frequencies, higher frequencies result in greater maximum penetration speeds, notwithstanding some observed discrepancies.

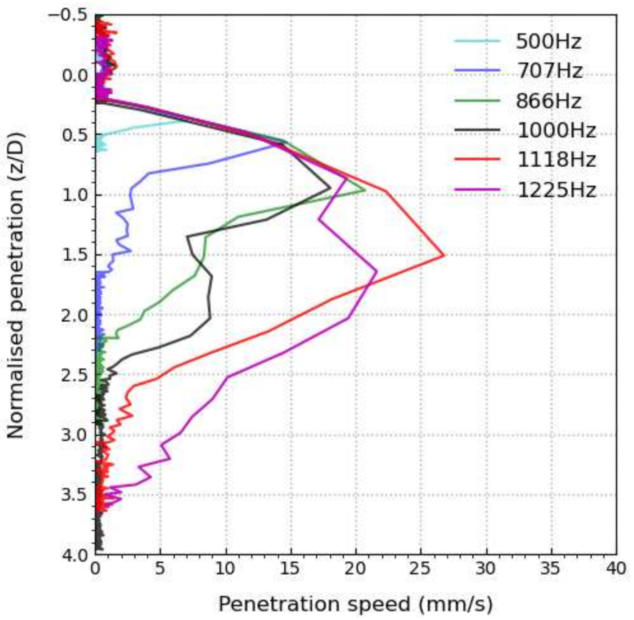

Figure 3 – Penetration speed variation along the normalised penetration for different vibrating frequencies

4 ANALYSIS OF RESULTS

Figure 4 presents the normalised penetration of the pile for the different frequencies at different driving times. Most of the penetration of the pile takes place in the first five seconds [4 min] of vibro-driving, and while the pile almost does not penetrate further at 500 Hz [10 Hz], at higher frequencies the penetration rate decreases with time but remains greater than zero for the duration of the experiments (up to 7 min [6 h] at 707 Hz [14 Hz]). To scale the results of Figure 4 to prototype dimensions, driving frequencies should be divided by 50, while the vibrating times should be multiplied by 50.

Noticeably, the penetration depth at a given time appears to be linearly linked to the frequency in the range of frequencies explored.

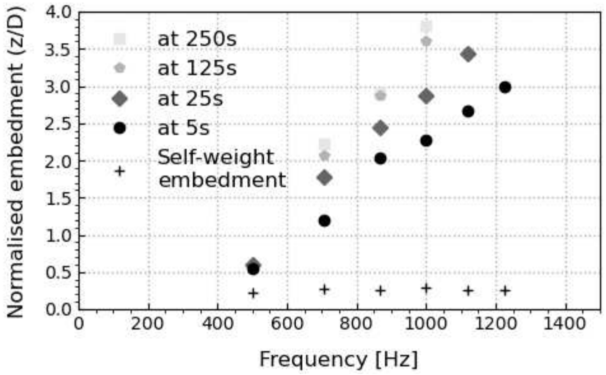

Figure 4 – Normalised penetration function of the vibrating frequency after different vibrating times in the centrifuge.

Small-scale tests at 1g have explored the influence of the frequency at a constant eccentric moment. Fang *et al.* (2024) observed an increase of the penetration rate and penetration depth with increasing frequency. However, the relationship between the variation of the frequency and the penetration is difficult to quantify. Schönit (2009) conducted small scale tests on H-beams at 20, 30 and 40 Hz, where the increase of frequency led to an increased penetration rate, which appeared to be approximately linear with frequency based on the graphical representation of the six penetration tests performed. Schönit (2009) also conducted field tests at 25, 30 and 40 Hz, showing an increase of penetration rate with frequency, but it is not as clearly quantifiable.

As underlined by Mazutti *et al.* (2024), Rodger and Littlejohn (1980) and Viking (2002) highlighted the importance for pile penetration of the full reversal of the tip resistance, which means that the vibrating force amplitude is large enough to counteract the self-weight of the pile-vibrohammer system, not mentioning the side-wall friction, to ensure upward movement of the pile during half of the vibrating cycle. The vibrating force amplitudes explored herein lay above and below the dynamic weight of the pile-vibro-driver system. Nonetheless, all tests conducted within this study see a pile penetration further than its self-weight penetration. This shows that the theoretical full reversal of tip resistance is not a necessary condition for the penetration during vibratory driving. However, it should be noted that the setup includes a counterweight and spring system that is directly tied to the vibro-driver platform by a dyneema rope. Their effects have not been measured during the experiments or considered in the theoretical dynamic weight of the system.

5 CONCLUSIONS

The FoundEx project explored the influence of driving, soil, and geometric parameters on the driveability of a miniature monopile by vibro-driving in sand, using TU Delft's geo-centrifuge. This paper focuses on the influence of the vibration frequency for a constant eccentric moment on the pile's driveability in a dry dense sand. The penetration depth and the penetration rate increased with the frequency of the vibrations. The penetration depth appears linearly dependent on the vibration frequency in this configuration. The exploration of different vibrating force amplitudes showed that the full reversal of the tip resistance is not a necessary condition for penetration during vibratory driving.

The FoundEx project explored a larger parametric space, including the eccentric moment, the static weight, the density of the sand, the role of fluid saturation with different viscosities, the centrifugal acceleration level, the sand type, and the pile wall thickness. The analysis of these tests is currently underway. Moreover, a lateral loading equipment compatible with the vibro-driver actuator is under development at TU Delft and should allow to explore the lateral behaviour of the pile in continuity after its in-flight installation. It will then be possible to explore the influence of the driving parameters on the lateral behaviour as well as study its evolution after cyclic loading. The availability of impact hammers for TU Delft's geo-centrifuge also paves the way towards a comparison of the pile lateral behaviour after impact and vibratory installation.

AUTHOR CONTRIBUTION STATEMENT

L.E.J. Simonin: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualisation, Writing – original draft. **H. Rattez**: Conceptualisation, Funding acquisition, Methodology, Resources, Supervision, Writing – review and editing. **W. Ovalle-Villamil**: Conceptualisation, Data curation, Investigation, Methodology, Project administration, Resources, Writing – review and editing. **M.A. Cabrera**: Conceptualisation, Formal Analysis, Methodology, Supervision, Writing – review and editing. **S. François**: Conceptualisation, Funding acquisition, Writing – review and editing. **G. Anoyatis**: Conceptualisation, Funding acquisition, Writing – review and editing.

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