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Investigation of vibro-driven monopiles in a geo-centrifuge

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ABSTRACT: In the context of ever-growing monopile foundation for offshore wind turbines, the use of vibratory driving for very large monopiles is gaining traction due to its potential to mitigate noise emissions, reduce fatigue of the pile, increase the pace of installation, avoid pile-run, and because it is easier to upscale than impact hammers. This research seeks to investigate industry-standard driving parameters and further, aiming to shed light on the driveability and post vibro-driven lateral behaviour of monopiles. Additionally, it aims to compare data against the predictions of existing driveability models, provide a comparison to centrifuge tests on impact-driven piles, and generate a crucial dataset for future numerical simulations of monopile installation and lateral loading. The experiments investigate vibratory pile driving within a scaled 50g environment at TU Delft geo-centrifuge as part of the GEOLAB project FoundEx. Firstly, the scaling of the vibro-driver is detailed, and the testing setup is outlined. Secondly, the performance of the vibro-driver for a standard case is assessed. The testing campaign will aim to explore a range of installation parameters, both for the soil (density, saturation) and the vibro-driver equipment (frequency, eccentric moment, static weight).

1 INTRODUCTION

The offshore wind (OW) market continues to grow in Europe, where the OW capacity was 30GW at the beginning of 2023, with 2.5GW installed in 2022 (Wind Europe, 2023). The average capacity of installed offshore wind turbines (OWTs) in 2022 was 8MW (Wind Europe, 2023), and the individual capacity of OWT will continue to rise in the future with plans for 14MW OWT for Hornsea 3 wind park (Ørsted, 2023).

Larger OWTs imply larger foundations, foundations that are predominantly monopiles (81% of bottom founded OWTs in 2020, Wind Europe (2021)), large open-ended steel tubes reaching diameters (D) over 10m, wall thickness (t) over 100mm, and length (L_{tot}) over 50m.

Monopiles are typically driven into the seabed with hydraulic impact hammers. However, as hydraulic hammers grow larger along with piles, there are concerns that pile driving by impact causes too much underwater noise thus harming the marine wildlife (Bailey *et al.*, 2010), and damages the pile. Also, increasing the size of impact hammers to match new XXL monopiles is challenging. Vibratory-driving for monopiles offshore has gained traction in the recent years both in the industry (e.g. projects listed on CAPE Holland's website (2023)) and in the research community (Da Silva *et al.* (2023), Mazutti *et al.* (2022a,b)), because vibratory-hammers lead to less noise emission and fatigue of the pile, in addition to the possibility of juxtaposing several vibratory-hammers to create a more powerful one, and potentially enabling faster driving as well. However, uncertainties around the effect of vibratory-driving on the subsequent lateral loading capacity of the monopile currently holds back this technology. Moreover, while industry standard parameters and software are used to select vibratory-hammers as a function of the soil and the pile characteristics, little research has been conducted to explore the vibratory-hammers parameters' range and its influence on the driving and lateral load capacity.

Installation of piles offshore has already been undertaken by vibratory-driving (records in Doherty *et al.* (2015), CAPE Holland (2023)). A few medium field scale test (GDP, see Metrikine *et al.* (2020), and the ongoing SAGE sand project, see Letizia *et al.* (2024)), small scale laboratory tests or field tests (Da Silva *et al.* (2023)), and centrifuge tests (Mazutti *et al.* (2022a,b)) have taken place.

Centrifuge testing is an interesting tool as the practicality of small-scale laboratory tests is associated to field-like stresses. No large centrifuge testing campaign has yet taken place to explore vibratory-driving in sand for monopiles and their subsequent lateral loading response.

This paper depicts a newly built mini-vibratory-driver at UCLouvain, preliminary results on the embedment of a miniature pile under 50g, and perspectives of a larger parametric study that is underway within the geo-centrifuge of TU Delft as part of the Geolab project FoundEx.

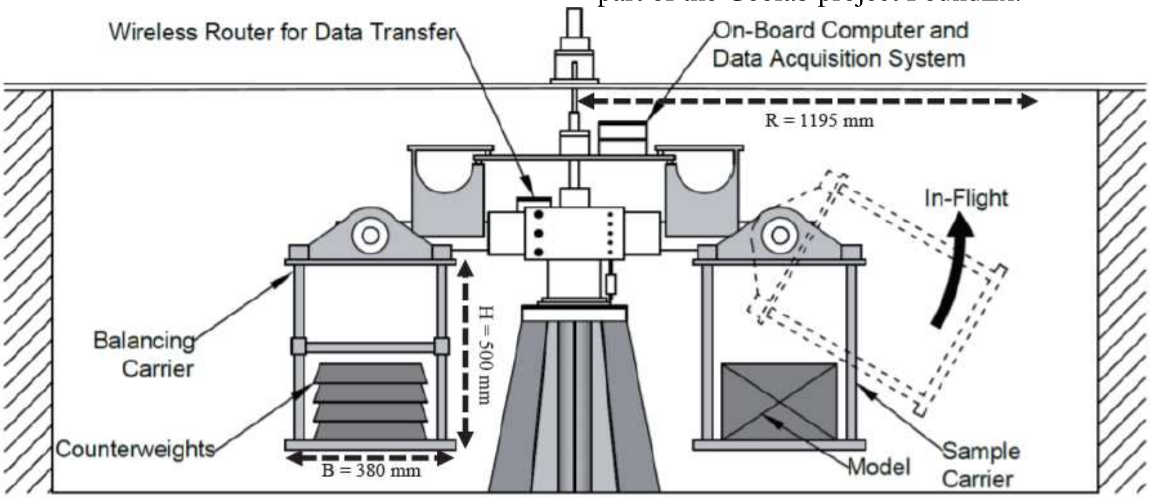

Figure 1. Schematic illustration of TU Delft's beam centrifuge (Li et al, 2020)

2 GEO-CENTRIFUGE

2.1 TU Delft Geo-centrifuge

This experimental campaign is part of the Geolab project, and takes advantage of the 9 ton.g beam centrifuge of TU Delft, illustrated in Figure 1.

The sandboxes used for the tests on dry sand have a 295mm internal diameter for a 190mm internal height, and a 20mm thick bottom plate. The sandbox is filled up to 30mm from the top, leading to 160mm high samples. The centrifugal reference radius is considered at a third of the sample depth.

Another sandbox, equipped for future saturated tests is available. It is pictured in Figure 2.

2.2 Scaling laws

The first objective of the experiment is to down-scale the foundation system geometrical dimensions by a factor N. This imposes a down-scaling of surfaces by a factor N^2, and of volumes by N^3.

The second objective is to be representative of the phenomena at play during its installation and lateral loading, which implies that the same type of soil (sand) and density, and pile material (steel) should be employed.

Scaling of interests are presented in Table 1 and are in agreement with previous studies (Mazutti, 2022a). The scaling factor that is used herein is N=50.

Table 1. Scaling factors

Quantity	Fundamental dimensions	Scaling factor
Length	L	1/N
Mass	M	$1/N^3$
Time	T	1/N
Frequency	T^{-1}	N
Acceleration	$L.T^{-2}$	N
Density	$M.L^{-3}$	1
Forces	$M.L.T^{-2}$	$1/N^2$

2.3 Driven pile dimensions

New OWTs are often founded on monopiles with diameters surpassing 10m, and wall thickness of approximately 100mm, with a low embedment of around three pile diameters, in water depths over 20m, resulting in structures weighting over 1000t.

In the centrifuge, it would imply a 100mm diameter monopile at 100g, or 200mm at 50g. TU Delft's geo-centrifuge cannot accommodate such size. Its main limitations are the diameter and the depth of the sandbox that can fit in the centrifuge basket. Because the pile should sustain lateral loading after driving, the diameter of the pile is even more limited to avoid boundary effects. The diameter of the sandbox to avoid boundary effects varies between studies, twelve diameters in Achmus *et al.* (2007), ten diameters in Al-biker *et al.* (2017), Richards *et al.* (2019), and Deckers and Defer (2023), or seven diameters in Leblanc *et al.* (2010) or Abadie (2015). In the case of Delft's geo-centrifuge and of the available sandbox, these imply maximum pile diameters of 25mm, 30mm, or 42mm.

Because of this constraint and the commercial availability of thin-walled tubes, a D=25mm diameter stainless steel tube (DIN 1.4301) with 0.5mm wall thickness is used. The wall-thickness to diameter ratio is 50, which is close to, but lower than, the API RP 2A-WSD (2014) standard that leads to ratios between 60 for a 1m diameter pile and 95 for 12m diameter piles, and lower than for recent offshore wind farms where ratios over 100 have been used.

To fit the vibro-driver experimental structure into the geo-centrifuge carrier, the pile length is limited to 210mm. While the theoretical tube weight is 55g, its geometrical inconsistencies result in a 60g weight.

The objective is to embed the tube by three or five diameters: 75mm or 125mm. These ratios are representative of current offshore practice.

Table 2 summarises these model quantities and presents the corresponding prototype quantities.

Note that the stainless-steel pile surface has not been further treated.

Table 2. Model and prototype dimensions of the driven pile for N=50

Quantity	Model	Prototype
Pile diameter	25mm	1.25m
Pile wall thickness	0.5mm	25mm
Pile height	210mm	10.5m
Pile weight	60g	7.5t
Embedment range	75-125mm	3.75-6.25m

2.4 Soil material and sample preparation

GEBA sand (SIBELCO, 2014), an industrial high silica fine sand, is used for the experiments. Its properties are presented in Table 3. The use of GEBA sand should allow for future comparison with impact hammering studies on the same material currently underway at TU Delft.

Samples are prepared by hand pluviation from a low height in four layers. Between the pouring of layers, shockwave compaction is used to densify the sample. The final density, D_R=80% herein, is reached via vibration on a shaking table.

Table 3. GEBA SAND material properties (Beroya-Eitner et al. (2022))

Parameter	Symbol	Value	Unit
Median grain size	D_{50}	0.119	mm
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	-

3 MICRO-VIBRO-DRIVER

3.1 Principle

A vibro-driver uses vertical vibrations to drive down into the soil the structure it is fixed to. These vertical vibrations are generated by (a) pair(s) of counter-rotating masses that produce a sinusoidal vertical force that provokes the pile-hammer system to move if it overcomes the soil friction. A more detailed description of the working principle can be found in Viking (2002) or Doherty *et al.* (2015).

3.2 Specifications

Simulations of the vibro-driving of a pile with the prototype dimensions up to a 5D embedment have been run in the commercial software GRLWEAP14 (Pile Dynamics (2024)) for a very dense dry sand with the API method. Based on these simulations, a vibratory hammer running at a frequency of approximately 20Hz with an eccentric moment of 25kg.m appears appropriate and just at the limit of being able to drive the prototype pile to a 5D embedment. Accordingly, scaling of this hammer for tests at 50g leads to a 4g.mm eccentric moment along with a 1kHz vibrating frequency (see Table 1).

Experimentally, it is also important to picture a representative static weight of the pile-hammer system. Thus, the hammer weight should not be disproportionally large compared to the pile weight (see real cases of vibro-driving by CAPE Holland (2023)). The standard case taken here is a vibro-driver weighing one-third of the theoretical pile weight.

The objective of the under-way experimental campaign at TU Delft is to explore the governing parameters of vibro-driving in sand. The design of the mini-vibro-driver should thus allow the variation of the vibrating frequency, of the eccentric moment, and of the static weight of the pile-hammer system.

3.3 Equipment

The main challenge for such a mini-vibro-driver resides in generating the standard vertical vibrating frequency of 1kHz. Several working principles were explored: electro-acoustic like systems, piezo-stacks, and high-speed miniature brushless DC-motors. The latter were selected as such motors are available off-the-shelf, while it would have been tedious to generate such forces with the other two systems.

Counter-rotating eccentric masses, as for real size vibro-hammers, are used. Using two motors to rotate two distinct shafts was discarded because of the complexity to synchronise them at 60,000rpm. Instead, tests were carried out to assess the possibility to use gears to link the leading shaft to the secondary counter-rotating shaft. Several materials were tested, and steel gears were selected. Due to their wear at these high velocities, they are regularly replaced during the testing campaign to avoid friction levels leading to overcurrent issues of the motor controller. The two shafts are supported by ball-bearings, and the leading shaft is linked to the motor via an Oldham elastic-coupling. Identical eccentric masses are set on each shaft. This set-up is illustrated in Figure 2.

To ensure the verticality of the driving, the vibro-driver is mounted on a platform equipped with two PTFE-lined bushings that run along two vertical linear shafts. With future tests campaigns in mind, the platform dismounts from these linear shafts before reaching the required embedment length to allow subsequent lateral loading.

The controller of the motor allows easy modification of the rotational velocity between tests, and the Maxon Group motor from the ECX SPEED series is able to reach up to 2kHz.

The eccentric masses can easily be replaced, and the following set of eccentric moments has been manufactured: 1, 2, 3, 4, 8, 28.6 and 200g.mm.

A counterweight is used to compensate the disproportionally large weight of the mini-vibro-driver (approx. 300g), reaching a more representative static weight for the whole pile-hammer system. This counterweight is linked to the vibro-driver with a Dyneema® rope through a pulley system. The counterweight rises vertically while the pile-hammer system slides down vertically. This means that, during spinning, both elements move through the acceleration field, the pile-hammer becoming heavier and the counterweight lighter. In consequence, a linear spring that imposes a tension equals to the difference in apparent weights (during centrifugation) between the initial and current positions of the two elements is used. The counterweight mass is adjustable such that its influence on the driveability can be explored. Accordingly, a range of linear springs is available to accommodate these different masses.

These different systems are supported by a frame that ensures the geometrical alignment of all parts.

Table 4 summarises the available settings for the mini-vibro-driver.

Table 4. Model and prototype dimensions of the vibro-driver for N=50

Quantity	Model	Prototype
Eccentric moments	[1;2;3;4;8; 28.6;200] g.mm	[6.25;12.5;18.75;25;50; 178.75;1250] kg.m
Max. frequency	2kHz	40Hz
Pile-hammer static weight	55g×[1;4/3;5/3; 2;8/3]$\times 50g$	6.9t×[1;4/3;5/3;2;8/3] $\times 1g$

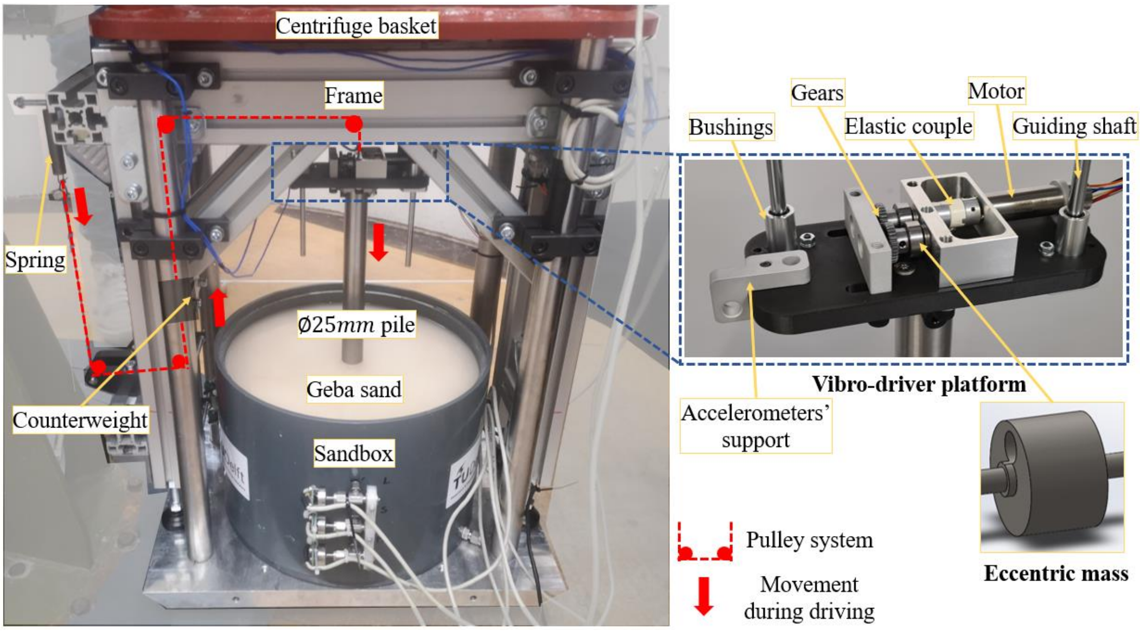

Figure 2. Picture and schematic of the mini-vibro-driver and its structure in TU Delft's geo-centrifuge basket.

3.4 Sensors

The vibro-driver platform is equipped with two 500g piezoelectric accelerometers that are placed on a dedicated support, pictured in Figure 2. One of the accelerometers is placed vertically to record the vertical vibrations, while the other is placed horizontally and perpendicularly to the axis of rotation of the eccentric masses to verify that eventual parasitic horizontal vibrations are minimal. The acquisition frequency is 4kHz, which is enough here because the vibrations are periodic such that capturing their envelope is enough to characterise them. The vertical accelerometer allows to derive the amplitude of the vertical vibrations. Also, a laser sensor fixed to the frame aims vertically at the platform to record the embedment at a sampling frequency of 100Hz.

4 PRELIMINARY RESULTS

Figure 3 presents the embedment of the pile under 50g in the standard case (frequency of 1kHz, eccentric moment of 4g.mm, and pile-hammer static weight of 4/3×55grams× $50g$) in a very dense dry sample (80% relative density).

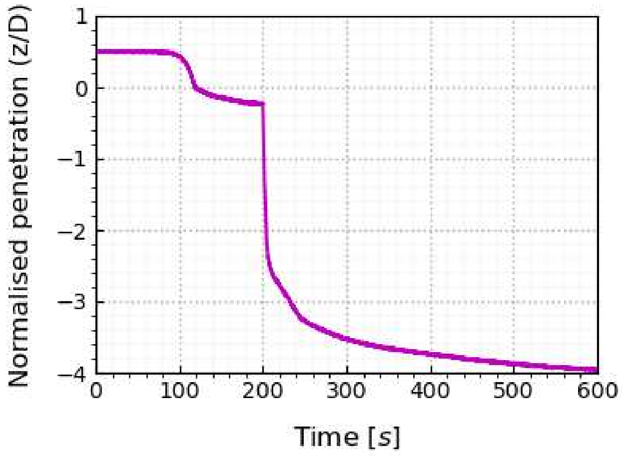

Figure 3. Normalised embedment (where D=25mm) versus time for the standard case

At the initiation of the spinning of the centrifuge, the pile is above the ground level (ordinate 0 in Figure 3). This is due to the presence of the spring. This configuration allows the spring, which has a pre-constraint force and a linear stiffness, to develop the right compensating tension during the driving of the pile under 50g. At approximately 90s, the pre-constraint of the spring is reached, such that the pile moves linearly until it touches ground at approximately 120s. It then slowly settles into the ground by approximately a fifth of a diameter under the increasing gravity. After 200s, 20s after a 50g acceleration is reached, the mini-vibro-driver activates, which provokes a rapid (8s) driving of the pile to 2.5D. The driving then progressively slows down and approaches asymptotically a 4D embedment.

5 CONCLUSIONS

This study presents the working and constructive principles of a new miniature vibro-driver for centrifuge studies on the driveability of piles into the ground.

Under 50g, this mini-vibro-driver should represent in its standard configuration (1kHz frequency, 4g.mm eccentric moment, 4/3×55grams× $50g$ static weight), a 1.25m diameter monopile driven at 20Hz by a 25kg.m vibratory-hammer. The mini-vibro-driver successfully drove a 25mm diameter hollow tube to 4D depth in this standard configuration for very dense dry GEBA sand.

Its driving parameters (*i.e.* frequency, eccentric moment, static weight) can easily be changed to explore their influence on the driving of the pile in sand. This constitutes the main objective behind the construction of this apparatus. Future research including the influence of the driving parameters on the subsequent lateral loading response of the pile, or the comparison with impact-hammer installation, is planned. This experimental campaign will constitute an essential database to investigate the capabilities of current driveability predictive tools as well as future numerical studies.

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