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Development of a mini vibro-driver to model monopile installation in a geotechnical centrifuge

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ABSTRACT: The installation of monopile foundations for offshore wind turbines (OWTs) by vibration is a promising alternative to the conventional impact-driven technique. However, significant uncertainties remain regarding monopile driveability and lateral pile performance after installation. Laboratory tests of vibro-installation, complementing field tests, have been limited to unit gravity. A vibro-driver designed for use in a geotechnical centrifuge would allow investigation of this complex soil-structure-interaction problem at stress levels relevant to the field. This paper presents some of the challenges faced during the development of a mini vibro-driver for use in a geotechnical centrifuge, noticeably related to scaling laws and provides results from an initial model monopile vibro-installation test.

Keywords: monopiles, vibro-driving, physical modelling, geotechnical centrifuge.

1 INTRODUCTION

Monopiles are the most popular foundation option for offshore wind turbines (OWTs), especially in shallow water depths. In Europe, monopiles accounted for more than 80% of all new installed OWT in 2020 (Wind Europe, 2020). The monopiles are conventionally installed by impact driving, a technique that requires the use of expensive and cumbersome noise mitigation systems (NMS) to reduce acoustic emissions exceeding allowable values. Vibro-driving is a low-noise technique, which does not require the use of NMS. It is time-efficient and cost-effective technique when compared to impact-driving.

Despite the advantages, vibro-driven monopiles are not yet widely used due to a lack of understanding of the soil mechanisms occurring during vibro-driving and its effect on the post-installation performance. The post-installation lateral response (stiffness and capacity) is especially important for monopiles supporting OTWs, which are dynamically sensitive structures. Vibro-installation is a complex soil-structure engineering problem and understanding the soil-structure behaviour is a critical aspect to reach predictability of the monopile performance (Doherty et al., 2015).

Modern vibro-drivers used to install monopiles (Figure 1) generate dynamic vertical oscillating forces through the counter-rotation of pairs of eccentric masses. The vertical vibrations are generated in the exciter block that is connected to a suppressor housing at its top, and to the monopile at its base through a clamping device. The vibro-driver is connected to the crane through a cable attached to its suspension hook. The suppressor housing isolates the vibrations from the vibro-driver to the crane.

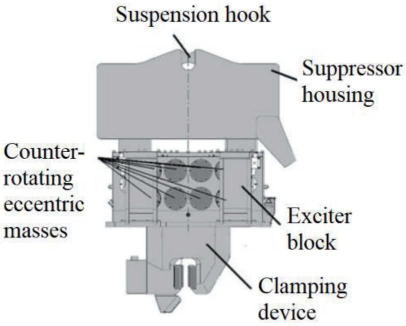

Fig. 1. Vibro-driver components (adapted from Whenham & Holeyman, 2012).

To be able to reproduce a vibro-driver in laboratory in model scale, a series of scaling considerations about the vibro-driving parameters must be taken into account. These parameters are explored in the following section.

2 DESIGN CONSIDERATIONS FOR THE MINI VIBRO-DRIVER

The mini vibro-driver was designed to work in a centrifuge environment, where a number of scaling relations need to be followed in order to retain similitude to the prototype. The main parameters affecting vibro-driving - identified so far - and considerations in the mini-vibro driver development are described below. A comprehensive and more detailed review of the vibro-driving parameters can be found in Viking (2002). The scaling laws for these parameters are presented in Table 1. To ensure relevance to field conditions, publicly available specifications of vibro-driven monopiles were reviewed, with the Riffgat project being the main available source through the study of Neef et al. (2013).

Table 1. Scaling laws.

Vibro-driving parameter	Unit	Scale factor
Pile and driver mass, m_o	kg	$1/N^3$
Static force, F_o	N	$1/N^2$
Dynamic force, F_{dyn}	N	$1/N^2$
Eccentric moment, M_e	kg.m	$1/N^4$
Vibrational frequency, f	Hz	N
Displacement amplitude, s_o	m	1/N

Mass and static force (m_o, F_o):

For a vibro-installed pile, the self-weight of the vibrating system (F_o) – i.e. the pile and the vibro-driver weight – and their mass (m_o) is critical for the installation response. The self-weight of the vibrating system in the centrifuge should be $1/N^2$ of the prototype to achieve similitude. This is normally achieved by reducing all pile dimensions by a factor N and using material of the same density as the prototype (so that the mass of the pile is $1/N^3$ of the prototype). Testing at Ng then ensures similitude as in conventional centrifuge scaling.

Dynamic force (F_{dyn}):

The dynamic force is the vertical oscillating force that drives the pile. It depends on the vibro-driver eccentric moment (M_e), rotational speed (ω) and rotational angle of the eccentric mass (θ) (Equation 2). The dynamic force is usually referred to by its maximum value, when $\theta=90^o$ or 270^o.

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

Eccentric moment (M_e):

The vibro-driver eccentric moment is a critical parameter on pile driveability. It is the sum of the eccentric moment of each single eccentric mass, i.e. mass (m_e) times eccentricity (e):

$$M_e = \sum m_e e \tag{3}$$

Manufacturers usually indicate the final value of M_e, not specifying m_e and e separately. Adopting the concept of eccentric counter-rotating masses, miniaturised for use in the centrifuge, (i.e. direct scaling of the eccentric moment) would require very small masses (of the order of the weight of a paper clip) at eccentricities of a fraction of a millimetre.

Vibrational frequency (f):

The vibrational frequency is the number of times the the dynamic load fluctuates in a second, i.e. the number of vertical cycles undertaken by the pile per second. It is related to the angular frequency (ω) by:

$$f = {}^{\omega}/_{2\pi} \tag{4}$$

There is no consensus on the impact of this parameter on the pile performance after installation, but there is an increasing interest on the investigation of using lower frequencies to install the pile. Achmus et al. (2020) found that for different operating frequencies during the seating phase of vibro-installation, lower values would lead to lower penetration velocities, less soil loosening, and consequently better soil post-installation conditions. Direct scaling of the frequency (see Table 1), which in the field is typically 23 Hz but for research purposes should be investigated over a wider range, results in impractical motor rotational speed requirements for the miniaturised vibro-driver in the centrifuge if counter-rotating masses are used.

Displacement amplitude (s_o):

The final (semi) displacement amplitude of the pile is a function of both the mass of the vibrating system and the eccentric moment of the driver:

$$s_o = {}^{M_e}/_{m_o} \tag{5}$$

Manufacturers usually specify the free hanging displacement amplitude of vibro-drivers, which usually considers the mass of the vibro-driver and clamp as m_o. To estimate the final displacement amplitude of the pile (in air), the mass of the pile must be included in m_o.

The vibrational amplitude has an important impact over the tip resistance behaviour during vibro-driving. Massarsch et al. (2020), Vogelsang et al. (2015) and Labenski (2020) suggest that full reversal of motion often occurs at the pile tip during vibro-driving. This penetration mode was first classified as "slow vibratory driving" by Rodger and Littlejohn (1980).

The final displacement amplitude of the pile was not a straightforward consideration when developing the mini vibro-driver. Holeyman et al. (2020) show monopile displacement amplitudes ranging from 1 mm to 5 mm. Displacement amplitudes of a fraction of a millimetre will be found when scaling s_o according to Table 1. The combined effect of the small displacement amplitudes, grain size and thickness of the pile over skin friction and tip resistance is not yet understood. Nevertheless, from the results obtained so far, the authors believe that full reversal of motion occurs, and that slow vibratory driving is replicated.

Summary of scaling considerations

Some of the parameters described are interrelated. For this reason, it is not straightforward to assess their isolated contribution on the pile vibro-driveability and the post-installation performance. Consequently, a system was designed to isolate the likely different parameters (e.g. m_o, F_o, F_{dyn}, f) during physical model testing and understand their importance was designed.

3 THE MODEL VIBRO-DRIVER

The model vibro-driver was developed to (i) be flexible to work for a range of different vibro-parameters; (ii) be compact, to fit on top of a model pile; and (iii) $F_{dyn}/F_o > 1$, so that full reversal of motion is possible. Synchronizing these objectives was a challenge. To achieve sufficiently high dynamic forces able to overcome F_o at a given g-level, the vibrational frequency must be much greater than prototype values.

To reach the desired frequencies using counter-rotating eccentric masses (as commonly used in field), two possibilities were considered: synchronising two motors, or using a suitable gearbox. Neither of these options proved to be practical at the required high motor rotational speeds. Instead, a new approach was proposed to generate high vibrational frequencies (Figure 2). A brushless motor on top of the system drives a pulley system connected to a profiled ('bumpy') wheel. The rotating wheel acts somewhat like the 'bumpy road' actuator initially used to model earthquakes in the centrifuge (Kutter, 1983).

The mechanism works by guiding a single vertical slider up and down by means of top and bottom bearings that follow the (diametrically opposed) undulations of the bumpy wheel. Using an odd number of undulations entails that when the top bearing is on a 'hump' of the undulations, the bottom bearing is in a trough etc. The undulations imply a displacement amplitude e to the slider of total mass m_e, that is equivalent to the total eccentric mass of standard counter-rotating eccentric mass systems. Because the slider is only allowed to move vertically, a single moving mass is sufficient to generate pure vertical dynamic loading and no synchronisation is needed.

However, to be able to generate repetitive oscillating forces at high frequencies (up to 400 Hz), the slider must travel smoothly along the wheel surface. If the slider bounces against the wheel, undesired vibrational frequencies are generated. For this reason, the bumpy wheel profile was carefully designed to deliver a sinusoidal vertical displacement to the slider. In addition, to match the scaling requirements for M_e, the slider had to be light but also robust, so it could withstand high dynamic forces and avoid breakages.

The main advantage of this system is that the vibrational frequency is proportional to the number of wheel undulations and the wheel rotation speed. For example, if the motor rotational frequency is 50 Hz and the wheel has 7 undulations, the generated vibrational frequency of the slider (and system) will be 7 x 50 = 350 Hz. This ensures motor speeds remain practical and that a light weight high powered motor can be used.

The device was designed to generate maximal dynamic forces of 2 kN, through a vibrating mass of 0.172 kg, an eccentricity of 0.7 mm and a frequencies up to 400 Hz. The bumpy wheel system allows the system to be light, compact and flexible, while still generating high dynamic forces. The vibrational frequency can be easily controlled by a custom-developed software that controls the motor speed, and alternatively, by modifying the number of undulations on the bumpy wheel. Other vibro-driving parameters such as m_e and e can be adjusted by changing the mass of the slider and the amplitude of the undulations.

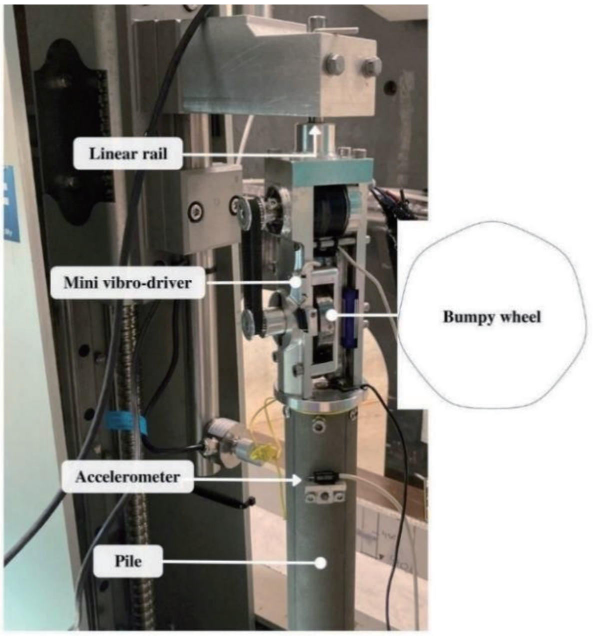

Fig. 2. Setup used for vibro-installation test.

4 INITIAL TEST RESULTS

Following detailed characterisation of the vibro-driver, mounted rigidly on a load cell, at different g-levels, a preliminary vibro-driven monopile test was carried out at the National Geotechnical Centrifuge Facility (NGCF) at the University of Western Australia (UWA), at an acceleration of 30 times the Earth's gravity (30g). The test was performed in dry UWA superfine silica sand (Chow et al., 2019), at a relative density of 95%. The steel pile had an external diameter of 50 mm, wall thickness of 0.5 mm and length of 500 mm.

The mini vibro-driver was mounted on the top of the pile (Figure 2), vibrated at a frequency of 340 ± 10 Hz, with an eccentric mass $M_e = 1.2 \times 10^{-4}$ kg.m and a total system mass $m_o = 1.51$ kg. During the test, the pile system penetrated the soil solely by self-weight and vibration, i.e. no additional vertical external force was applied. A laser was installed on the vertical actuator, targeting the top of the mini-vibro driver, in order to track the system vertical displacement. To ensure vertical installation, a rod was installed at the top of the mini vibro-driver. During installation, the rod slid through a vertical linear rail connected to the vertical actuator. The vibrator-pile system was not connected rigidly to the actuator.

An accelerometer was mounted on the pile, at a distance of 50 mm from the pile head. A high-speed data acquisition system tracked the acceleration amplitudes of each vibratory cycle during the installation process. This data allows the investigation of the development of acceleration amplitudes and vibrational frequencies over the duration of the test. An extract of the acceleration measured during vibro-installation is presented on Figure 3. The measured acceleration amplitudes are repeatable and agree reasonably well with the design values. The predicted accelerations of 37 ± 2 g lead to dynamic forces of 550 ± 30N, dynamic pile displacement amplitude of ± 0.07 mm and F_{dyn}/F_o of about 1.2. During the whole installation, the displacement and acceleration amplitudes were approximately the same. The test was considered successful, reaching an installation depth of 137 mm in 60 seconds.

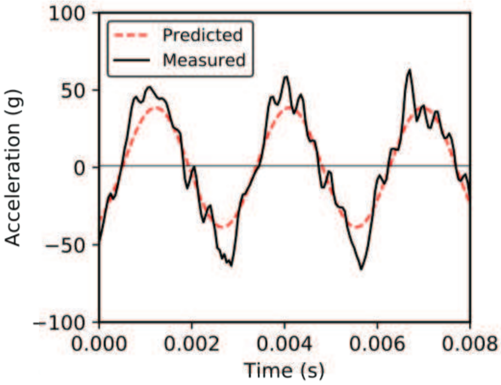

Fig. 3. Pile acceleration predicted and measured during vibro-installation test (g = 9.81 m/s2).

4 CONCLUSIONS

A mini vibro-driver was designed and commissioned, taking into consideration centrifuge scaling laws and fundamental principles of vibro-driving. This paper has described some of the challenges faced during its development and a successful vibro-installation test. The device is flexible and can work in a range of different vibro-parameters.

A vibro-installation test was performed at 30g. The mini vibro-driver was attached to the top of a model monopile and the system penetrated by vibration and self-weight during installation, being guided vertically by a linear rail. The installation was tracked cycle-by-cycle by an accelerometer mounted on the model monopile, showing consistent and repeatable results.

The mini vibro-driver opens a wide range of possibilities for investigating the performance of vibrated piles. Further testing is underway to understand the mechanisms underpinning vibro-driving in sand.

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REFERENCES

Achmus, M., Schmoor, K. A., Herwig, V. & Matlock, B. 2020. Lateral bearing behaviour of vibro- and impact-driven large-diameter piles in dense sand. *Geotechnik 43, 3.*

Chow, S. H., Roy, A., Herduin, M., Heins, E., King, L., Bienen, B., O'Loughlin, C., Gaudin, C. & Cassidy, M. 2019. Characterisation of UWA superfine silica sand. V1.

Doherty, P. & Prendergast, L. J. & Gavin, K. 2015. Comparison of Impact Versus Vibratory Driven Piles: With a focus on soil-structure interaction. *Deep Foundation Institute*.

Holeyman, A. & Whenham, V. 2020. Vibratory Driving of a Monopile at a North Sea Site. *Deep Foundation Institute*.

Kutter, B. L. 1983. Deformation of centrifuge models of clay embankments due to 'bumpy road' earthquakes. International Journal of Soil Dynamics and Earthquake Engineering 2(4):199-205.

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

Massarsch, K. R. & Weräll, C. & Fellenius, B. H. 2020. Vibratory driving of piles and sheet piles – state of the practice. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering, paper 2000127.*

Neef, L. & Middendorp, P. & Bakker, J. P. J. 2013. Installation of Monopiles by Vibrohammers for the Riffgat Project. *Pfahlsymposium, 187–201,* Braunschweig.

Rodger, A. A. & Littlejohn, G. S. 1980. A study of vibratory driving in granular soils. Géotechnique 30(3):269-293.

Van Dorp, R. & Moscoso, N. & Bielefeld, M. & Verbeek, G. 2019. The Use of Vibratory Driving of Foundation Piles for Offshore Applications – State of the Practice. *Deep Foundations Institute*.

Viking, K. 2002. Vibro-driveability - a field study of vibratory driven sheet piles in non-cohesive soils. Doctoral thesis, *Royal Institute of Technology*, Stockholm, Sweden.

Vogelsang, J., Huber, G. & Triantafyllidis, T. 2015. On Soil Deformation and Stress Redistribution Around Pressed-in and Vibrated Displacement Pile Tips. *Holistic Simulation of Geotechnical Installation Processes. Springer International Publishing Switzerland 2015.*

Whenham, V. & Holeyman, A. 2012. Load Transfers During Vibratory Driving. *Geotech. and Geol. Engineering 30:1119-1135.*

WindEurope. 2020. Offshore Wind in Europe.