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Impact of monopile hammering installation on the horizontal response in centrifuge

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ABSTRACT: Monopiles used as foundations for offshore wind turbines are widely installed into the seabed by impact driving. This study examines the impact of hammering on the subsequent horizontal response of 1/100 scale monopile model by using a large-beam geotechnical centrifuge. A special device including small-scale hammer was designed to install monopiles with 50 mm in diameter to an embedment depth of 250 mm in flight, and then to apply lateral loading on the monopile head without stopping the centrifuge. Tests findings from two horizontal loadings are discussed, with the monopile either Jacked monotonically at 1*g* or impact driven at 100*g*. The results highlight the need to consider the impact of installation on the horizontal monopile response.

Keywords: Monopile, Impact-driven installation effect, Horizontal response, Centrifuge modelling, Sand.

1 INTRODUCTION

Monopiles used as foundations for offshore wind turbines (OWTs) are widely installed into the seabed by impact driving. For Fatigue limit state design, the system natural frequency, governed by the foundation stiffness, is important to be accurately estimated (Arany et al., 2016). The foundation stiffness is significantly influenced by the changes of the soil state, including horizontal stress and the void ratio, due to the installation process (e.g. Fan et al., 2021b; Heins and Grabe, 2017; Maatouk et al., 2021; Murphy et al., 2018).

In the literature, centrifuge tests have been used to study the monopile response by using different methods of installation including jacking and impact driving (e.g. Dyson and Randolph, 2001; Klinkvort, 2012). Whereas, these tests required stopping the centrifuge to mount the lateral loading apparatus, which led to a loss of the state of soil post installation. Recently, Fan et al. (2021a) developed a miniature device allowing the post-installation state of the soil to be retained in centrifuge modelling. They revealed that the global lateral response of the monopile in dry sandy environments was altered by the installation process, and this was numerically confirmed by Bienen et al. (2021) and Fan et al. (2021c). However, the impact of the installation method on monopile horizontal response is still not well understood to provide guidance to the industry for the design of laterally loaded monopiles.

This study focuses on the effect of impact-driven installation of the monopile on its subsequent horizontal response in saturated dense sand. This was achieved using a developed experimental device that can carry out, in centrifuge at 100*g*, the impact-driven installation of a monopile model 50 mm in diameter to an embedment depth of 250 mm (5*D*), followed by lateral loading.

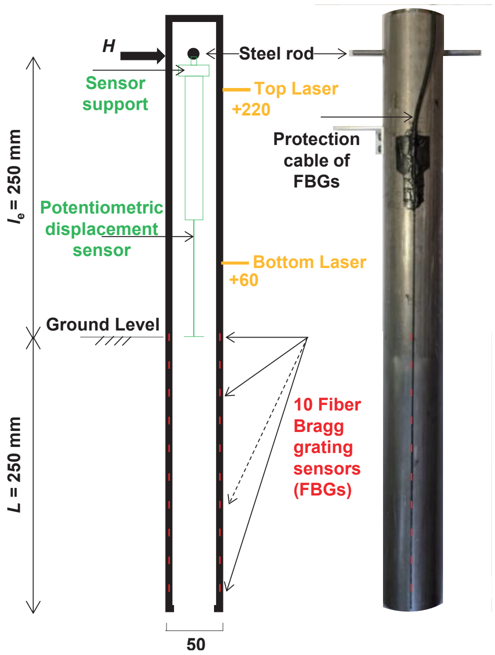
2 CENTRIFUGE TESTS

The experimental tests were conducted in a large beam geotechnical centrifuge (radius 5.5 m) at the Gustave Eiffel university. The tests were carried out at 100 times the Earth's gravity (N =100) on a large monopile model.

2.1 Monopile model and instrumentation

Details of the monopile model and instrumentation have been provided by Maatouk et al. (2021). The aluminium open-ended monopile model has an external diameter (D) of 50 mm, an embedded depth (L) and a load eccentricity (l_e) of 250 mm (i.e. 5D) and a wall thickness of 2.5 mm.

As developed by Li et al. (2020), ten pairs of Fiber Braggs Grating sensors (FBGs) were implemented inside the monopile thickness in the direction of loading to measure the axial strains induced throughout the loading, which in turn give the bending moment of the monopile at ten different levels (F. 1). Besides, two laser displacement transducers were positioned in front of the monopile (F. 1) to measure the horizontal displacements throughout loading. The monopile was also instrumented by a potentiometric position sensor (F. 1) to measure the internal height of the soil column during installation to observe if plugging was occurred.



F. 1. Photograph and longitudinal section of the instrumented monopile model.

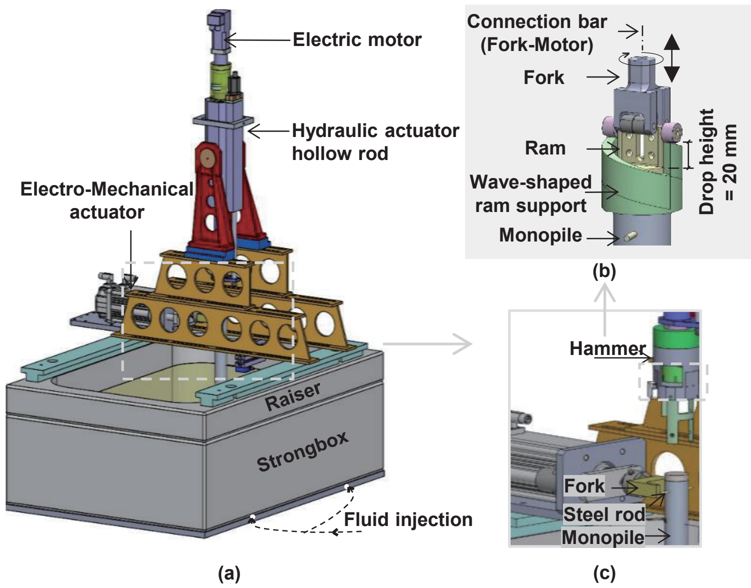


Fig. 2. (a) Experimental set-up; (b) details of the hammering process; (c) details of the lateral loading.

2.2 Experimental campaign

Two monotonic horizontal tests were carried out at 100*g* on the monopile model installed using two different methods. The first test, so called 'ID100g', was installed by impact driving at 100*g*, whereas the second one, so called 'J1g', was jacked at 1*g* (e.g. Li et al., 2021) and used just for comparison to quantify the impact of driving installation on the monopile response. A summary of the tests performed is given in Table 1.

The sequence of the test procedures starts from sample preparation, then, monopile installation ending with load application.

2.3 Sample preparation

The sample was prepared by using the raining deposition technique over a rectangular strongbox. A relative density of 82% ± 1.4% was obtained with the poorly graded NE34 Fontainebleau sand model used (Maatouk et al., 2020).

A 120-mm-high raiser (Fig. 2a) was fixed over the strongbox once it is completely filled up. The sample was then tap water saturated at 1*g* through four draining channels located at the bottom of the specimen (Fig. 2a).

Table 1. Details of tests performed.

Test	Installation phase	Loading phase
ID100g	Impact driving @ 100*g* with 5 blows/s	Monotonic loading @ 100*g* with 0.1 mm/s
J1g	Monotonically Jacked @ 1*g* with 1 mm/s	Monotonic loading @ 100*g* with 0.1 mm/s

2.4 Driving Monopile installation

The impact driving installation was conducted in flight at 100*g* using an electro-mechanical hammer monitored by a hollow hydraulic actuator to follow the descent of the monopile (Fig. 2).

The principle of the hammer was relied on a combined spin-upward movement of the ram before the free fall. The rotation of the ram was achieved by spinning the fork that is linked to an electric motor through a connection bar located inside the rod of the hydraulic jack. Both shapes of the fork and the ram support enable the ram upward movement through rotation.

The model delivered energy at 1*g* was 0.032 J per stroke. This was done using a ram model of 0.164 kg weight with a drop height of 20 mm (Fig. 2b).

2.5 Monopile horizontal loading

Following installation, for both tests, the vertical actuator was lifted up (Fig. 2c) to create the required clearance around the monopile head for the lateral loading phase. The main difference being solely the stress state induced by the installation of the monopile beforehand. For 'J1g' test, the centrifuge was ramped up, only for the lateral loading phase. Whereas, for 'ID100g' test, the horizontal loading was applied directly, without stopping the centrifuge after the installation, to retain the induced post-installation soil sate.

Lateral loading was applied to the centre of the cross-section of the monopile by pushing the steel rod that crossed the monopile perpendicularly to the direction of loading (F. 1) by using a fork attached to the horizontal electro-mechanical actuator (Fig. 2c).

3 IMPACT DRIVING RESULTS

The cumulative number of blows (n) and driving energy (ξ), defined by Maatouk et al. (2021), are plotted in prototype scale in Fig. **3** against the normalised settlement of the monopile.

The designed set-up was not able to suspend the monopile above the sand surface throughout ramping up the centrifuge and before the impact-driven installation. Hence, the monopile penetrated initially around 0.65D (s_0) under its own weight before being driven. Then, impact driving started, during which the blows number as well as the delivered energy required per unit meter penetration increased with the penetration depth. 3846 blows were needed to drive the monopile up to 5D.

During the monopile installation, the potentiometric displacement sensor revealed that the soil enters the monopile at the same rates as it advances. Therefore, no plugging was occurred during in flight installation.

4 IMPACT OF DRIVING MONOPILE ON LATERAL RESPONSE

For both installation methods, the global monopile behaviors are shown in prototype scale in Fig. **4**. These represent, at ground level, the horizontal load H_G and bending moment M_G as functions of the normalised displacement of the monopile y_G/D and its rotation about the neutral axis θ_G. The monopile deflection and rotation were obtained using a procedure derived from the FBGs and top laser displacement measurements as detailed in Maatouk et al. (2021). Both qualitative and quantitative comparisons are made.

4.1 Qualitative comparison

In both tests, two different trends are observed:

- For small loading amplitudes, the lateral resistance enhanced until $\theta_G = 0.7°$ or $y_G = 0.03D$ (i.e. 0.15 m).
- After that, this enhancement became less marked.

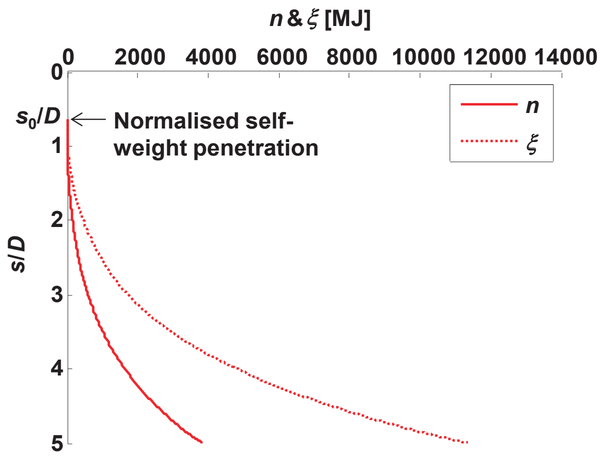


Fig. 3. Number of blows (n) and cumulative energy (ξ) at the prototype scale plotted against the normalised settlement of the monopile.

The improvement (Δ) brought by the in-flight impact-driven installation are also presented in Fig. **4**. This improvement corresponded to the difference of the lateral resistance between tests as normalised by the monopile resistance in the J1g test. Initially, this improvement was much more pronounced and can be explained by an increase of the horizontal stress along the shaft of the monopile during driving installation compared to that derived from 1g installation. Then, in the second phase after the dashed line, Δ decreased progressively until stabilization for high loading amplitudes mobilizing the soil far away. The results are consistent with the findings obtained by Fan et al. (2021a).

4.2 Quantitative comparison

Two relevant criteria were chosen to quantify the effect of impact-driven installation on the lateral response of the monopile:

- $\theta_G = 0.5°$: serviceability limit state requirement for OWTs (DNVGL, 2016).
- $y_G = 0.1D$: ultimate limit state for large deformations.

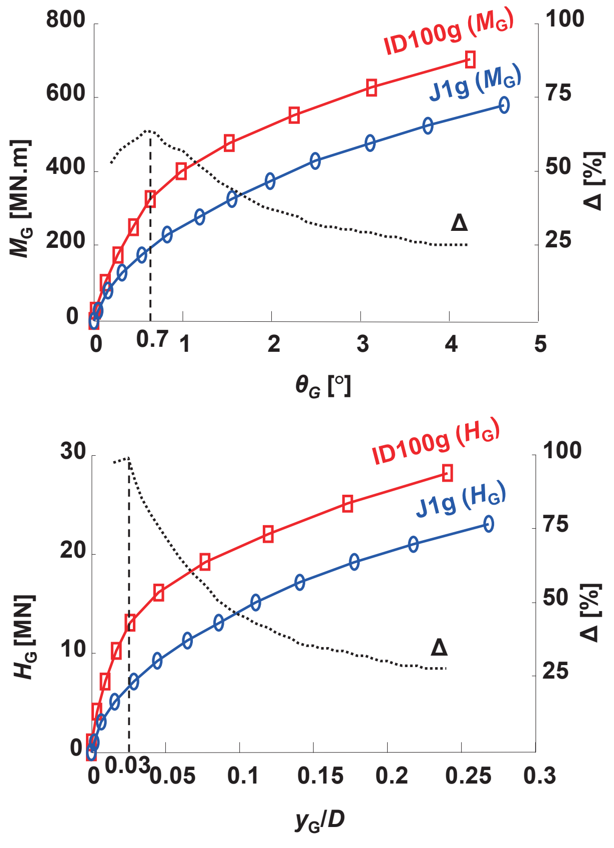


Fig. 4. Ground-level bending moment and load against the corresponding rotation and deflection of the monopile.

The secant stiffness at θ_G = 0.5° and the lateral resistance mobilised at y_G = 0.1D are summarised in Table 2. The in-flight installation improved the secant stiffness by 1.6-2.1, whereas the lateral resistance increased by 45%. The lateral resistance obtained in our study is slightly higher than that reported by Fan et al. (2021a), who obtained a value of 31% for a 3.1D embedding into dry sand with a relative density of 38% and l_e = 3.8D.

Table 2. Lateral secant stiffness and resistance at $\boldsymbol{\theta_G}$= 0.5° and $\boldsymbol{y_G}$= 0.1D respectively.

Test	Secant stiffness		Lateral resistance	
	k_{M_θ} [MN.m]	$k_{H\_y/D}$ [MN]	M_G [MN.m]	H_G [MN]
ID100g	541	553	515	20.6
J1g	337	259	355	14.2

5 CONCLUSIONS

A new set-up has been developed to combine, in centrifuge at 100g, the impact driven installation of a monopile model 50 mm in diameter to a depth of 5D, followed by horizontal loading.

To quantify the impact driven installation effect on the global monopile response, two methods of installation were explored —impact driving at 100*g,* and monotonically jacked at 1*g*—into water-saturated dense sand.

The impact of driving was more localised in the monopile vicinity, and was more pronounced for a narrow range of lateral displacement. This enhancement decreased progressively as the resistance increased until reaching a plateau for high loading amplitudes mobilizing the soil faraway from the monopile.

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