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1G scaled model of impact driving and lateral behavior of offshore monopiles

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ABSTRACT: To address the need for comprehensive understanding of impact hammering in monopile installation in the offshore industry, this study employs a 1G experimental setup that represents the driving and the lateral loading of an offshore monopile at a reduced scale. The setup includes piles of 6 cm and 11 cm diameter, equipped with fiber optics, an impact hammering system, and a lateral loading system. The installation phase and subsequent lateral loading are meticulously recorded using sensor technology. In addition, numerical models are employed to study the dynamic behavior of the 1g scale test and are used to further optimize the test setup. The study's findings encompass force-displacement under lateral monotonic loading. Also, the study emphasizes how different driving parameters affect the installation process and the lateral loading response.

1 INTRODUCTION

The global drive towards sustainable energy solutions has placed offshore wind energy at the forefront of the renewable energy sector's expansion, crucial for sustainable energy solutions, and relies heavily on monopile foundations to support wind turbines (WindEurope, 2021). Design of OWT monopiles is mainly controlled by lateral loading considerations, and recent advances have led to significant improvement in their design under monotonic loading, and thus to material and cost savings (B. W. Byrne et al., 2015; Abadie, 2015; Richards, 2019). Despite the effectiveness of the predominantly used impact hammering for monopile installation, it poses challenges like noise pollution and concerns over pile durability, highlighting the need for ongoing research.

Small-scale 1G laboratory tests are used to study real-scale monopile driving response through the use of adequate scaling laws, thus ensuring model-to-prototype similarity. However, achieving geometric, kinematic, and dynamic similarities in a 1g model test is challenging, often requiring prioritization of specific conditions (Wood, 2003; Bhattacharya et al., 2011; Konkol, 2014). Also, to provide better insight into the dynamic behavior and full-scale response of monopiles, numerical modeling is employed.

This paper aims to experimentally investigate the response of monopiles with diameters of 6 m and 11 m through a 1G test, utilizing scaled models of 6 cm and 11 cm diameter piles. The study focuses on understanding how the driving and lateral responses of these piles are influenced by three key parameters: the weight of the ram, the pile diameter, and the embedment length-to-diameter ratio (L/D). Additionally, we present a linear numerical model that is employed to accurately scale the force applied during the tests, ensuring a proper understanding of the impact these parameters have on pile behavior.

The paper begins by outlining the laboratory setup, including the sand container, the impact loading system, and the lateral loading system, and discusses experimental results on how driving parameters influence the driving process and piles' lateral behaviour. Then, the numerical model for calculating impact force on piles and its application to scaled models is explained. The paper concludes by summarizing key findings, contributing to current broader research of the authors to assess monopile driveability and their lateral response under both impact hammering and vibratory driving.

2 NUMERICAL MODELING

2.1 Impact hammer model

The impact hammer model, derived from (Deeks & Randolph 1993) analytical solution, evaluates pile head force during impact driving. This model, initially validated in (Wehbe et al. 2023) is employed to predict pile driving forces. It conceptualizes the system with lumped ram and anvil masses, a cushion with internal damping, and a dashpot-represented pile. Key elements include the ram, cushion, and anvil. The pile is modeled as a dashpot with impedance Z, defined by the pile's cross-sectional rigidity ($A_p E_p$) over wave speed (C_p). The model introduces a cushion, modeled as a linear spring and dashpot, to ensure uniform energy distribution. System dynamics are captured through equations considering the ram and anvil masses, cushion stiffness (k_c), damping (c_c), and initial ram velocity (v_0). The exerted pile force (F_p) is calculated by the product of pile impedance and ram velocity.

2.2 Application to the scaled model

As emphasized earlier, working with reduced-size models necessitates an accurate scaling of the studied parameters. Since the objective is to be as representative of the full-scale conditions as possible, the choice of an example Menck MHU 3500S hammer, formerly used to drive 6 m diameter piles in the Hornsea Project One offshore wind farm in the UK is used to downscale the full-scale hammer force. Figure 1 shows that the force at pile head of the prototype is 160 MN for a duration of impact of around 20 ms. As explained in Wehbe et al. (2023), for a scaling factor of N=100 for lengths in the laboratory, the hammer mass should be scaled by a factor or 1/N^3. The resulting force should be scaled a by factor 1/N$^{2.5}$, and the impact time by a factor of 1/N. These correspond at the small-scale to a force of 1.6 kN during an impact time of 0.2 ms due to the application of a ram size of 0.175 kg. However, for the purpose of facilitating the driving process through a manually feasible number of blows, larger masses were considered in this study within which a blow rate of 30 blows/minute was maintained.

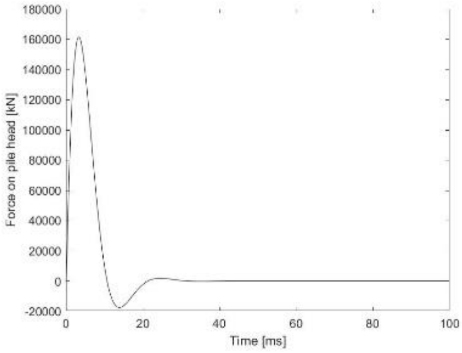

Figure 1 Force-time history for the prototype impact hammer force at pile head

3 EXPERIMENTAL SETUP

3.1 Sand container

In the design of the laboratory setup, initially developed by (Jafari 2020), for scaled monopile testing, a circular steel container was employed for dense sand with relative density D_r = 68%, a dry unit weight γ_{dry}= 1640 kg/m^3, and a saturated unit weight γ_{sat}= 1920 kg/m^{3,} representative of the densities of the soils met in the North Sea. The container's dimensions, 110 cm diameter and 125 cm height, were chosen to minimize boundary effects, aligning with recommendations from numerical and experimental studies (Achmus et al., 2007; LeBlanc et al., 2010; Abadie, 2015; Albiker et al., 2017; Richards, 2019) and accommodating model piles of 6 cm and 11 cm diameters, both with a wall thickness of 1.5 mm.

To enhance the fidelity of soil condition simulation, a sand pluviation system made up of two steel plates that can slide to let open holes of 13mm diameter for a 30 mm spacing. A diffuser mesh is placed 150mm under these plates, and the whole system is lifted 750 mm above the container to allow sand particles to reach their terminal velocities, drawing on the methodologies of (Hariprasad et al. 2016 and Richards 2019). This mesh, made of expanded metal with 10×5 mm openings, was validated experimentally in Deckers and Defer (2023) to significantly improve sand density and distribution uniformity. In saturated sands tests preserving the sand's homogeneity without disruption is crucial during the saturation process (Hoffman et al. 2020), therefore a water valve at the container's base is used to facilitate a slow saturation as it directs water through a 7 cm gravel layer, evenly dispersed below a geotextile barrier.

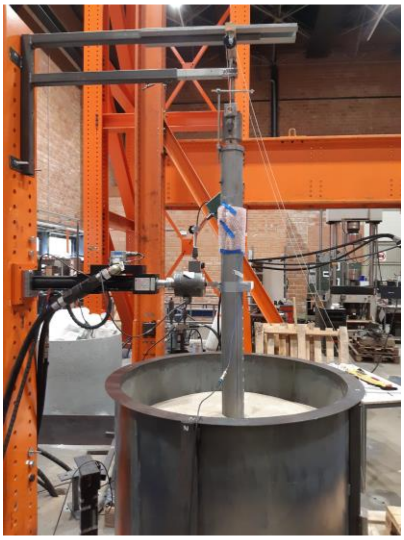

Figure 2 Laboratory setup present at UC Louvain

3.2 Impact driving system

In this study, a manual impact driving system, shown in Figure 3, was developed for model monopile testing, incorporating a guiding rod for vertical alignment and a spirit level to ensure precise positioning. The system used rams of varying masses (1.2 kg to 7.4 kg) to explore different impact driving dynamics. A cushion, placed between the ram and the anvil, optimized energy transmission and minimized rebound, with its efficiency supported by an analysis based on (Deeks and Randolph 1993). The system also included an anvil and a drop height limiter. Additionally, a pulley system facilitated the ram's elevation, and a 10000 g accelerometer fixing support was implemented for accurate acceleration measurements at the pile head. A laser optic sensor tracked the pile's embedment depth, ensuring precise data collection throughout the driving process.

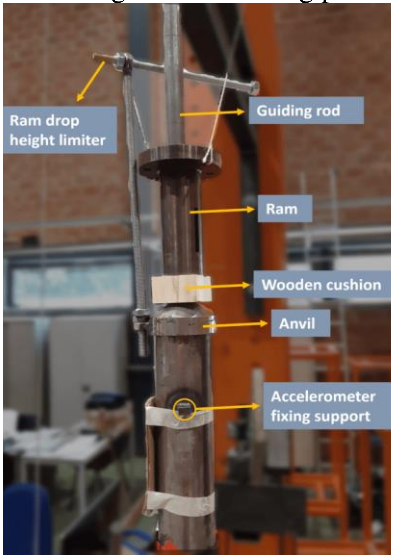

Figure 3 Components of the impact driving system

3.3 Lateral loading system

The second test phase, the lateral loading of the model monopiles, involves applying a horizontal force at a specific height to simulate the loads experienced by full-scale offshore monopiles. This force is applied using a computer-controlledhydraulic actuator with a 25 kN capacity and a 150 mm stroke length. A load cell attached to the actuator measures the force, and a small wheel connected to the load cell minimizes friction between the device and the pile, serving as the sole contact point. The actuator's loading speed, set at a constant velocity of 0.4 mm/s, allows for detailed analysis of the force applied to the pile against its displacement, measured at three locations as shown in Figure 4. Optic fibres with 1.3 mm gage pitch and an acquisition frequency of 80 Hz are used to measure the strains along the testing piles.

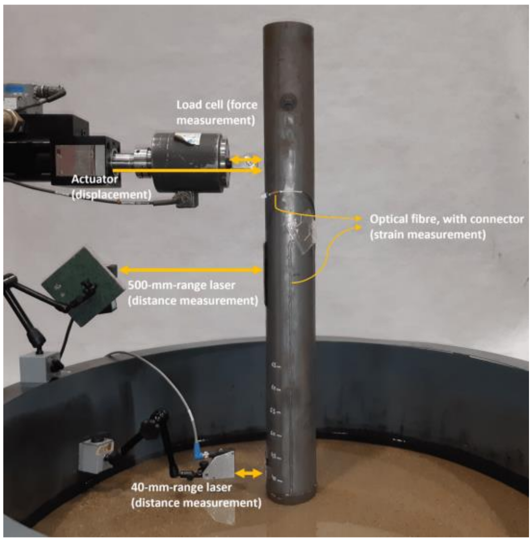

Figure 4 Pile setup for lateral loading

4 EXPERIMENTAL RESULTS ON THE EFFECT OF IMPACT DRIVING PARAMETERS

4.1.1 Mass of the ram, m_r

The experimental tests reveal that increasing the ram mass used in impact driving of monopiles, both in dry and saturated sand conditions, leads to a quicker embedment process, requiring fewer blows to achieve the same depth, as evidenced by the steeper curves in the embedment versus number of blows analysis in Figure 5. Despite variations in the lateral loading response due to different ram masses, the discrepancies in the pile's response are relatively minor, indicating that while the ram mass influences the driving process, its impact on the pile's lateral response is limited as shown in Figure 6. The consistent findings across tests with varying ram masses underscore the possibility to optimize the ram mass to increase driving efficiency without consequences on the lateral behavior.

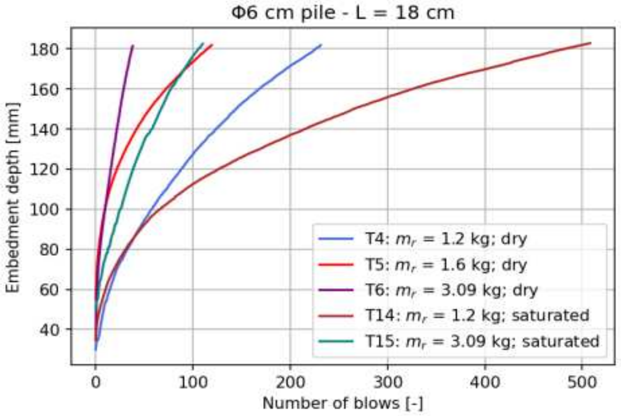

Figure 5 Number of blows vs. the embedment depth for the Ø6-cm pile (in dry and saturated sand) up to an embedment depth of 18 cm using different masses

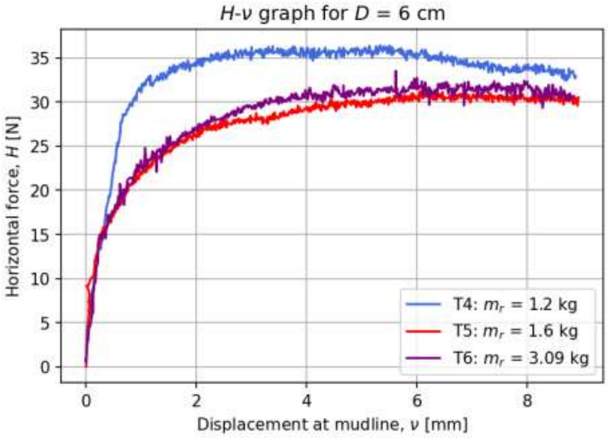

Figure 6 Horizontal Force H vs. the displacement at mudline v for the 6 cm diameter pile driven using 1,2 kg, 1.6 kg and 3.09 kg ram masses, respectively.

4.1.2 Pile diameter, D

The experimental tests examining the impact of pile diameter on driving and lateral responses reveal that smaller diameter piles in dry sand require fewer blows to achieve a certain penetration depth compared to larger diameter piles, attributed to increased friction with diameter (Ahmed et al., 2022). However, in saturated sand, this trend reverses, as shown in Figure 7, with smaller diameter piles needing more blows. This counterintuitive result is currently being further investigated. Lateral loading tests results (Figure 8) further indicate that larger diameter piles exhibit higher soil resistance and stiffness due to mobilizing a larger soil volume and increased embedded length, aligning with findings by Alderlieste et al. (2011) that larger diameters significantly enhance static lateral capacity.

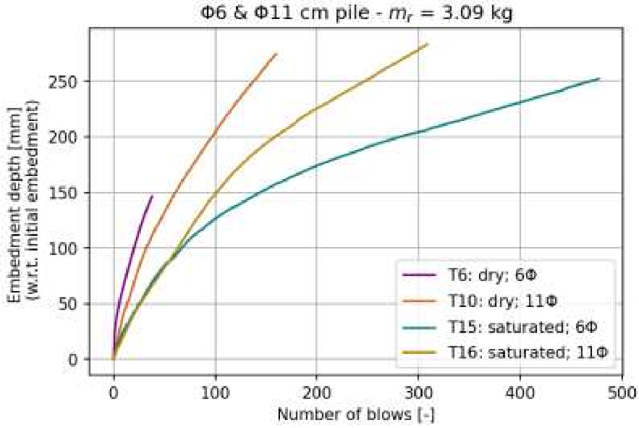

Figure 7 Number of blows vs. the embedment depth, where the initial embedment of the piles have been set as the new zero-value on the y-axis for comparison purposes.

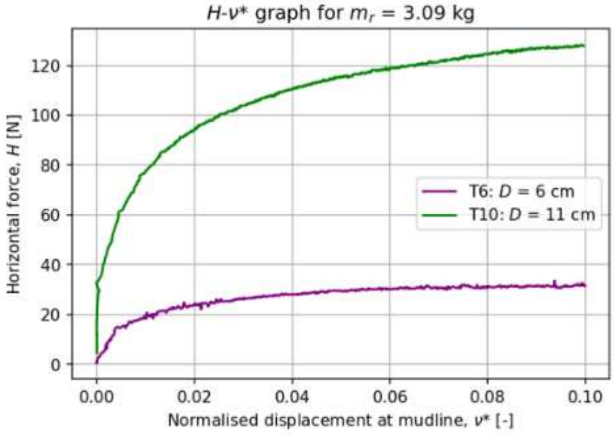

Figure 8 Lateral response of the 6 cm and 11 cm diameter pile employing the same mass of the ram.

4.1.3 Embedment depth to diameter ratio, L/D

The experimental tests explore the impact of the L/D ratio on soil resistance and the effect of varying L and D values on the soil's response to monotonic lateral loading. Higher L/D ratios, as demonstrated in tests with both 6-cm and 11-cm diameter piles, result in significantly greater soil resistance due to the larger soil volume mobilized by deeper embedment. Interestingly, despite variations in L and D, the lateral behavior of the soil is consistently governed by the L/D ratio, indicating that the ratio, rather than the absolute values of L and D, dictates the soil's response in both dry and saturated conditions. This finding underscores the critical role of the L/D ratio in monopile foundation design.

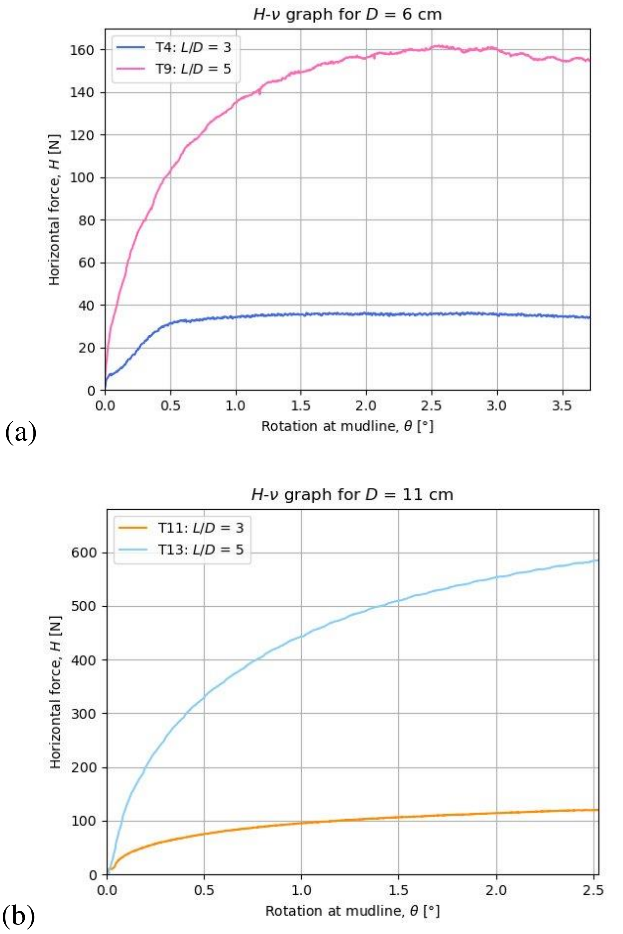

Figure 9 Horizontal force vs. Displacement at mudline for tests with varying L/D ratios for the 6 cm pile (a) and the 11 cm pile (b).

5 CONCLUSIONS

This paper presents of monopile behavior through 1g tests on 6 cm and 11 cm diameter models, representing 6 m and 11 m monopiles. By analyzing the effects of ram weight, pile diameter, and embedment length-to-diameter ratio on driving and lateral responses and employing a linear numerical model for force scaling. Results show that the pile diameter and embedment length to diameter ratio influence both the driving process and the lateral response of monopiles whereas the weight of the ram only affects the driving process.

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