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Impact of driving techniques on the lateral behavior of offshore monopile foundations

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Summary

This paper investigates the effect of bottom boundary conditions on the lateral response of impact-driven monopiles in dry sand through 1g model testing. Monopiles were installed in a compacted Fontainebleau sand mass with varying clearances beneath the pile tip. Results show that reduced h_s increases driving resistance and lateral stiffness due to artificial confinement from the rigid base. The study highlights the importance of considering vertical boundary effects when designing small-scale experiments on monopile behavior.

1 Introduction

Monopile foundations are the most widely used support structures for offshore wind turbines due to their simplicity and cost-efficiency, particularly in sandy seabeds of the North Sea [1,2]. While impact hammering remains the standard installation method, the accuracy of small-scale physical modeling of such processes is often limited by boundary effects inherent to 1g laboratory setups [4,5]. This study presents the results of a reduced-scale experimental campaign focusing on the monotonic lateral response of impact-driven monopiles in Fontainebleau sand. The analysis emphasizes the influence of bottom boundary conditions, particularly the thickness of sand beneath the pile tip (h_s), on the measured load–displacement behavior.

A similar issue arises in real offshore projects, such as the Calvados wind farm in France, where monopiles are driven into pre-drilled sockets through soft sediments into stiff or rocky layers [12]. This configuration increases tip confinement and stress wave reflections, requiring higher driving energy and potentially affecting pile behavior. These field conditions reflect boundary effects also seen in 1g lab tests with limited soil thickness beneath the pile tip, which can artificially enhance stiffness and complicate interpretation [11].

The next sections details the experimental setup, loading protocol and discusses the role of h_s in affecting driving resistance and lateral stiffness, supported by installation energy data and comparative load responses.

2 Experimental Setup and Testing Methodology

The experimental tests were carried out in a cylindrical tank. The soil mass consisted of Fontainebleau NE34 sand compacted layer by layer to reach the target relative density of 53%. Each layer was prepared by depositing exactly 18.4 kg of dry sand [5], which was then manually compacted to reach a uniform thickness of 50 mm.

To study the influence of bottom boundary conditions, the vertical distance between the pile tip and the tank base (h_s) was controlled by wooden plat of 2 and 4cm as shown in Figure 1.

The installation was performed using a simplified impact hammering system. A mass of 2.7 kg was dropped from a height of 100 mm, delivering 2.65 J of energy per blow. The number of blows required to reach the target penetration depth was recorded for each configuration of h_s . As shown in Figure 2 (b), the number of blows decreased as h_s increased, confirming the relevance of bottom boundary effects even during installation.

At the end of the pile installation, a lateral loading was applied at the pile head using a rotating motor with a cable under displacement-controlled conditions. A displacement rate of 0.44 mm/s was adopted to ensure quasi-static conditions and the force was recorded by a force sensor (Schlumberger U7000) and the displacement was taken through three different points in order to get more accurate results and verify the rigidity of the pile.

The key geometrical, material, and loading parameters of the setup are summarized in Table 1.

Table 1: Summary of experimental parameters

Parameter	Value
<i>Tank and Soil</i>	
Tank diameter	550 mm
Tank height	730 mm
Sand type	Fontainebleau NE34
Relative density (I_d)	53%
Compacted layer thik.	50 mm
<i>Monopile Geometry</i>	
Pile diameter (D)	80 mm
Wall thickness (t)	2 mm
Slenderness (D/t)	40
Embedment ratio (L/D)	3
Embedded length (L)	240 mm
<i>Impact Driving Method</i>	
Drop mass	2.7 kg
Drop height	100 mm
Energy per blow	2.65 J
<i>Bottom Boundary Conditions</i>	
Depth below tip (h_s)	146, 226, 266 mm
Blows to reach L	62, 58, 55

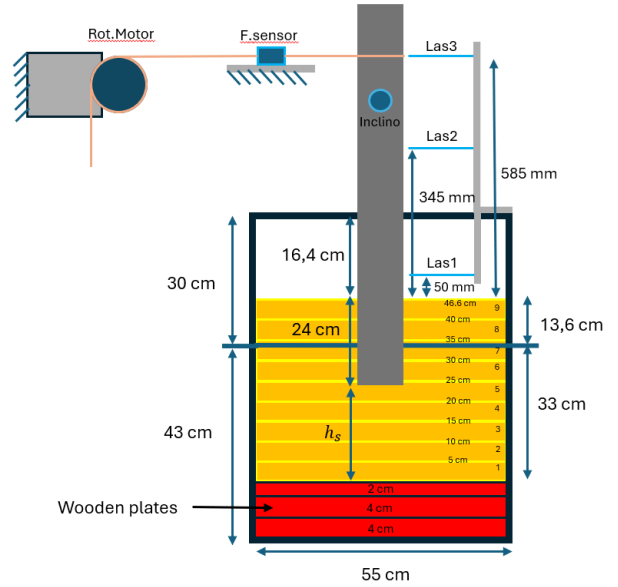


Figure 1: Experimental tank and pile setup.

To investigate the influence of bottom boundary conditions, the vertical distance between the pile tip and the tank base—denoted h_s —was systematically varied. The selected values (146 mm, 226

mm, and 266 mm) correspond to h_s/D ratios ranging from 1.8 to 3.3, where D is the pile diameter. According to numerical studies by Achmus et al. [8], a clear space of at least 2 to 3 pile diameters is typically needed beneath the pile to minimize the reflection of stress waves and boundary-induced confinement effects. Experimental works such as those by Leblanc et al. and Abadie [9, 10], also confirm that insufficient soil thickness below the pile may result in overestimated pile stiffness and bearing capacity due to stress wave reflections and artificial constraint from the rigid tank base. As h_s decreases, the interaction between the pile and the rigid bottom boundary becomes more significant, leading to an upward shift in stress distribution and lateral confinement. This effect can reduce the representativeness of the load–displacement response compared to free-field conditions. The tested configurations thus aim to quantify the extent of such boundary interference and to identify a threshold beyond which the bottom effect becomes negligible. Figure 2 (a) provides an illustration of the tested h_s configurations.

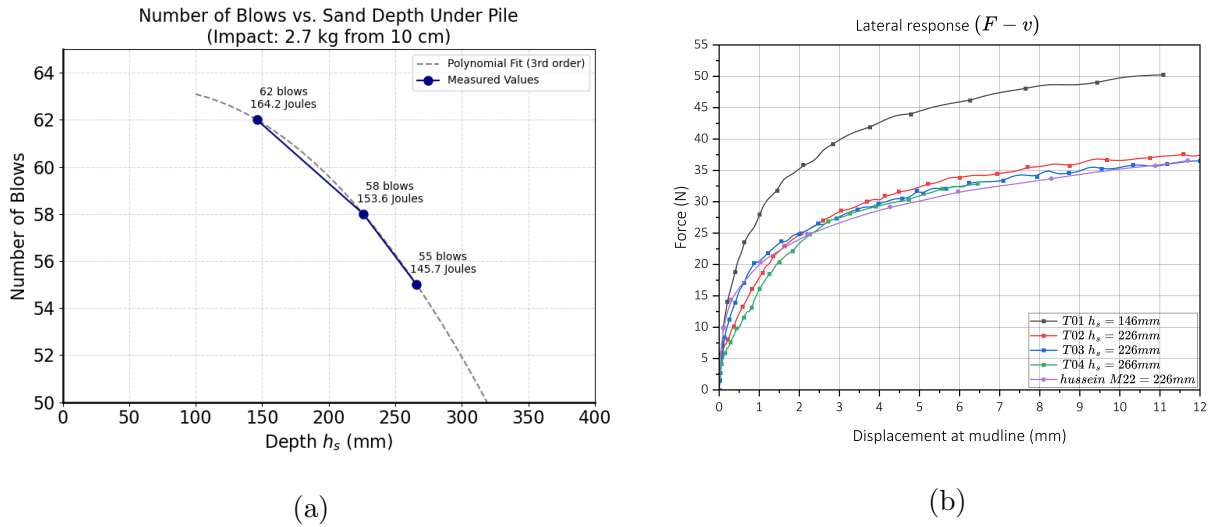


Figure 2: (a) Number of blows required vs. h_s , highlighting increased driving resistance with reduced clearance beneath the pile tip. (b) lateral response under varying h_s with Hussein test [5].

3 Conclusion

This study presents a preliminary experimental investigation into the lateral behavior of impact-driven monopiles installed in dry Fontainebleau sand (this choice was justified by Bakri and L.Kerner [4, 5]) under varying bottom boundary conditions. A reduced-scale 1g setup was developed to replicate monotonic lateral loading on piles subjected to impact hammering installation process. Special attention was given to the distance between the pile tip and the rigid tank base (h_s), which was varied across three configurations to evaluate its influence on both the installation effort and the mechanical response.

The results show that reducing h_s increases the number of blows required for full penetration, confirming that stress wave reflections and boundary-induced confinement significantly affect driving resistance. Similarly, monotonic lateral load–displacement curves indicate that lower h_s values lead to artificially stiffer responses, emphasizing the importance of sufficient clearance below the pile to ensure realistic and representative soil–structure interaction.

These findings highlight the critical role of vertical boundary effects in 1g small-scale experiments. They suggest that a bottom clearance of at least $2.5\text{--}3D$ is necessary to mitigate artificial confine-

ment and obtain results that are transferable to field-scale conditions. This work lays the groundwork for further testing involving vibratory driving and cyclic loading, with the long-term goal of improving experimental protocols and enhancing the accuracy of monopile foundation modeling in offshore wind applications.

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