Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 4940-4947

ECCOMAS
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COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

SCALING AND MODELING OF AN IMPACT PILE DRIVING 1G LABORATORY SCALE TEST

Tamara Wehbe[1,3], George Anoyatis[2], Hadrien Rattez[3] and Stijn François[1]

[1]KU Leuven, Department of Civil Engineering, Structural Mechanics Section
Kaastelpark Arenberg, 40 Box 2448, 3001 Leuven, Belgium
tamara.wehbe,stijn.francois@kuleuven.be

[2] KU Leuven, Department of Civil Engineering, Hydraulics and Geotechnics Section
Campus Bruges, 8200 Bruges, Belgium
george.anoyatis@kuleuven.be

[3] UC Louvain, Institute of Mechanics, Materials and Civil Engineering
GCE, Place du Levant, 1348 Louvain-la-Nauve, Belgium
hadrien.rattez@uclouvain.be

Abstract. *The widespread deployment of offshore wind turbines requires the use of fast, low-cost and reliable foundation installation methods. Despite the fact that vibratory driving provides an adequate alternative to the predominantly used impact driving technique, lack of data concerning the effects of impact driving on the lateral behavior of foundations in the short and long term indicates a need for a detailed study to understand the parameters influencing the procedure and how it could be improved. For this purpose, a small-scale well-controlled impact pile driving in a sand filled container experiment has been developed and numerically simulated. Numerical models are employed to study to dynamic behavior of the 1g laboratory scale test which allows for better understanding of the test setup. The numerical model includes a multi-body dynamic model to compute the force response on the pile head. Furthermore, scaling laws are derived to provide the best correspondence with a full-scale numerical model from the laboratory scale model. These include scaling the pile dimensions as well as the quantities that alter the force applied on the pile head. Results obtained allow us to optimize the current laboratory setup.*

Keywords: Offshore Wind Turbines, Scaling laws, Impact Pile Driving, Numerical Modeling

ISSN:2623-3347
Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10772.21219

1 INTRODUCTION

Offshore wind power is a rapidly growing industry and a key component in the transition towards a more sustainable energy future. Monopiles are the most popular foundation type for offshore wind turbines due to their simple design, cost-effectiveness, and ease of installation. The installation of monopiles typically involves several stages and methods, which can vary depending on the site-specific conditions, such as water depth, soil conditions, and wind conditions. The most common method for installing monopiles for offshore wind turbines into seabed is impact hammering. A large hydraulic hammer is used to drive the monopile into the seabed until it reaches a specified depth. The hammering process though creates vibrations that can cause noise and potentially harm marine life. Mitigation measures are often taken to reduce the impact. Vibratory driving is an appealing alternative which is recently gaining more ground in offshore applications. It involves using a vibrating pile driver to embed the monopile into the seabed. This method present many advantages such as faster installation, reduced noise and vibration than hammering. However, it may not be suitable for all soil types, although recent developments have resulted in powerful vibratory hammers.

This study focuses on the analysis of the drivability mechanisms during impact driving, and is part of a broader research effort of the authors which aims to assess both installation methods for offshore applications to monopiles, by means of theoretical developments and laboratory tests. To analyze pile drivability under impact driving, an analytical solution was originally developed by Deeks & Randolph [1], This model has been successfully applied to dynamic large diameter pile driving numerical models [6], experimental models of impact driving [4] and numerical modeling of ground borne vibrations [8] and provides an adequate estimate for pile driving characteristics. In this work, the Deeks & Randolph model is solved numerically. In this regard, a numerical model is implemented in Matlab, using the toolbox Stabil [2]. At first, comparisons with the analytical model in terms of force-time response due to hammer impact validate the proposed formulation. Then the model is used to design a 1G laboratory test, presented in Figure 1. A discussion on scaling laws is provided. The prototype impact pile driving system presented in Deeks & Randolph is herein down-scaled to a laboratory pile driving set up. Results obtained from the numerical model are shown for both the prototype and the scaled model for the time history of the force applied at the pile head due to the hammer impact. Finally, a discussion on the envisioned laboratory test is provided. Such physical modelling is a first approach to gain further understanding in the phenomenon of impact pile driving for offshore applications, which in a second phase will be extended to account for saturated soil conditions and vibratory hammers.

2 THEORETICAL INVESTIGATION

2.1 Proposed numerical model and validation

The force at the head is computed by means of the model originally developed by Deeks & Randolph [1]. The model is based on lumped ram and anvil masses separated by a cushion with internal damping, and connected to the pile which is modelled as a dashpot. The main components of the system are the ram, the cushion, and the anvil as shown in Figure 2. The solution models the pile as a dashpot of impedance Z:

$$Z = \frac{A_{\mathrm{p}} E_{\mathrm{p}}}{C_{\mathrm{p}}} \tag{1}$$

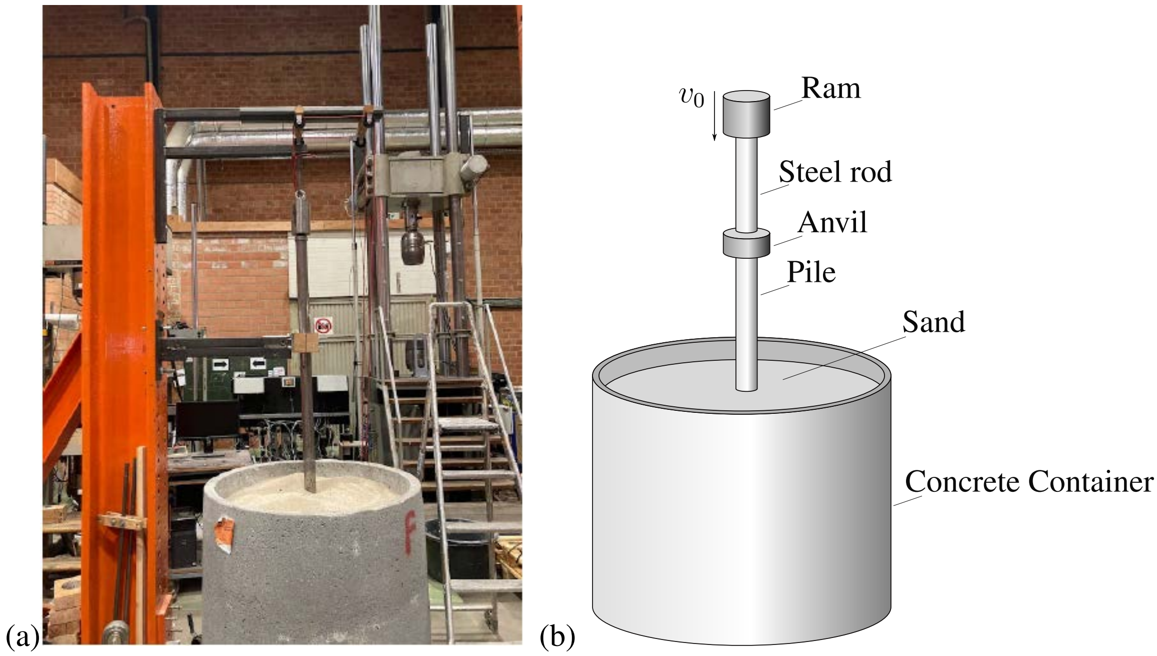


Figure 1: Laboratory setup: a) Physical model at the laboratory in UC Louvain and b) Schematic representation of the main components of the test.

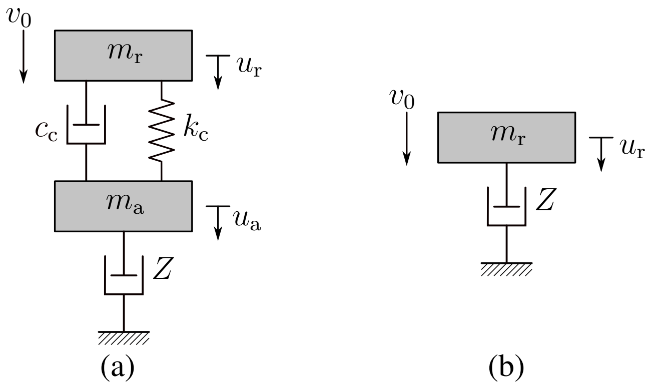


Figure 2: Deeks and Randolph model (a) for a ram with a cushion and anvil and (b) without cushion and anvil.

where $A_\mathrm{p}E_\mathrm{p}$ is the pile's cross-sectional rigidity, and C_p is the (one-dimensional) wave speed in the pile. To account for the fact that in practice the cushion deforms non-linearly, and absorbs energy, Deeks & Randolph used a combined linear spring in parallel with dashpot for the cushion (Fig. 2). The equations of motion of the system are written as

$$m_\mathrm{r}\ddot{u}_\mathrm{r} + c_c(\dot{u}_\mathrm{r} - \dot{u}_\mathrm{a}) + k_c(u_\mathrm{r} - u_\mathrm{a}) = 0 \tag{2}$$

and

$$m_\mathrm{a}\ddot{u}_\mathrm{a} + Z\dot{u}_\mathrm{a} + c_c(\dot{u}_\mathrm{a} - \dot{u}_\mathrm{r}) + k_c(u_\mathrm{a} - u_\mathrm{r}) = 0 \tag{3}$$

where m_a is the mass of the anvil and u_a its displacement (pile head displacement), cushion stiffness k_c and internal damping c_c. The initial conditions of the system are $\dot{u}_r = v_0$ and $u_r = 0$. The force exerted on the pile F_p is obtained by multiplying the pile impedance by the ram velocity, as shown below

$$F_\mathrm{p} = Z\dot{u}_\mathrm{r}^* \tag{4}$$

The system of equations can be alternatively written in matrix form as follows:

$$\underbrace{\begin{bmatrix} m_\mathrm{r} & 0 \\ 0 & m_\mathrm{a} \end{bmatrix}}_{\mathbf{M}} \underbrace{\begin{bmatrix} \ddot{u}_\mathrm{r} \\ \ddot{u}_\mathrm{a} \end{bmatrix}}_{\ddot{\mathrm{u}}} + \underbrace{\begin{bmatrix} c_\mathrm{c} & -c_\mathrm{c} \\ -c_\mathrm{c} & Z + c_\mathrm{c} \end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix} \dot{u}_\mathrm{r} \\ \dot{u}_\mathrm{a} \end{bmatrix}}_{\dot{\mathrm{u}}} + \underbrace{\begin{bmatrix} k_\mathrm{c} & -k_\mathrm{c} \\ -k_\mathrm{c} & k_\mathrm{c} \end{bmatrix}}_{\mathbf{K}} \underbrace{\begin{bmatrix} u_\mathrm{r} \\ u_\mathrm{a} \end{bmatrix}}_{\mathrm{u}} = \begin{bmatrix} m_r v_o \\ 0 \end{bmatrix} \quad (5)$$

The solution is obtained numerically using the direct time integration method. In this regard, the Wilson-theta method is implemented in the Matlab toolbox Stabil [2]). The analysis yields results for the nodal displacements u, the velocities $\dot{u}$ and accelerations $\ddot{u}$ of a dynamic system with mass **M**, damping **C** and stiffness **K** matrices, subjected to external excitation **P**. At time $t = 0$, the ram hits the pile head with a velocity $v_{drop} = v_0$. To ensure numerical stability, the parameters α, δ and θ in the Wilson-theta method are set equal to 0.25, 0.5 and 1, respectively. The time window t is equal to 0.1 s and the time step Δt is set equal to 0.0001 s, which is small enough to ensure the stability and the precision of the integration scheme.

The performance of the numerical model is validated through comparisons with results obtained from the model of Deeks & Randolph. Figure 3 shows results in terms of force time history. In their original work, a BSP 357 hammer was used to drive a 762 mm diameter pile of 18.5 mm wall thickness, and an equivalent impedance of 1750 kNs/m. The cushion was steel with a stiffness of 1.6×10^6 kN/m, whereas the cushion damping is neglected. The ram and anvil masses for this hammer were 6860 kg and 850 kg, respectively. The results for the variation of the pile head force with time are in perfect agreement.

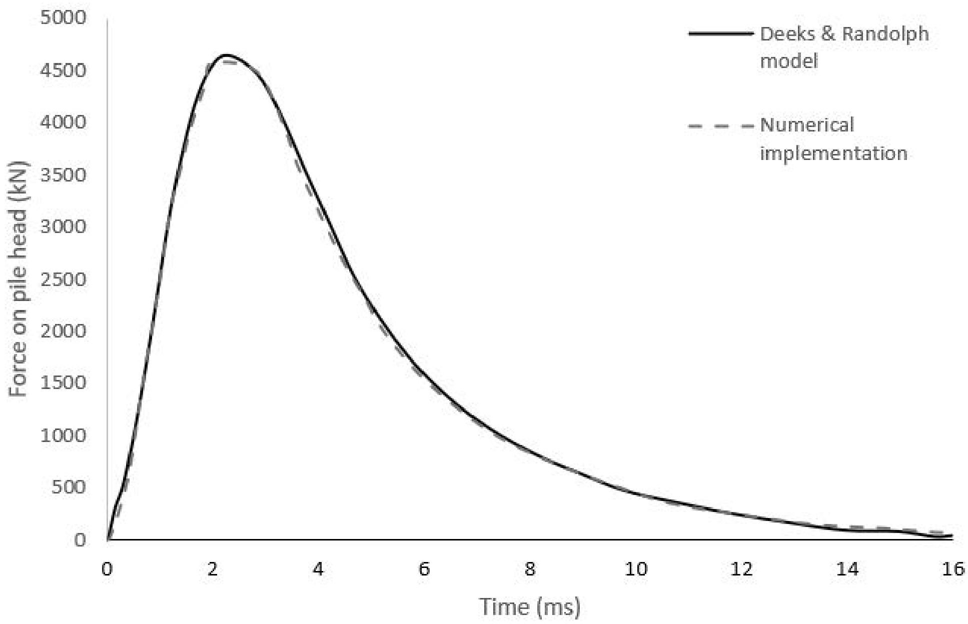


Figure 3: Variation of pile head force-time response with time; dashed line: Deeks & Randolph model [1], solid line: proposed numerical model.

Impact hammering without cushion As a first step in the envisioned laboratory setup, no anvil is installed. In this case, the system reduces to a single degree of freedom (SDOF) system, as shown in Figure 2 (which is also due to the same stiffness of the ram and the anvil). Thus the equation of motion of the system dully reduces to:

$$m_r\,\ddot{u}_r + Z\,\dot{u}_r = 0 \tag{6}$$

2.2 Scaling laws and experimental test design

Scaling laws are mathematical relationships that describe how the physical properties of an object or system change as its size or scale changes [7]. In the hammer-pile impact system adopted in this study, three quantities should be scaled: the mass of the ram, the pile impedance and the falling velocity of the ram. The self-weight of the hammer, which is represented by the ram in the 1G scale test should be scaled by a factor of $1/N^3$. This is achieved by scaling down all pile dimensions by a factor N, using the same pile material as in the prototype. As a result of the pile diameter being reduced by $1/N$, the cross sectional area of the pile is reduced by $1/N^2$. The pile impedance is thus reduced by $1/N^2$. The mass drop velocity is scaled by a factor of $1/\sqrt{N}$. This is achieved by scaling the length of the free fall by $1/N$, and thus the duration of free fall by $1/\sqrt{N}$. The scaling of the duration of impact, scaled by $1/N$ is in accordance with the scaling of the length of the pile, which is also scaled by $1/N$. Consequently, the scaling of the force on the pile head, which is the product of multiplying the pile impedance by the velocity at which the ram hits the pile head is concluded to be $1/N^{2.5}$. This complies with Newton's second law and assuming no energy loss in the ram-anvil-pile system. Table 1 provides a summary of the scaled quantities. Herein the prototype model presented in Deeks

Impact-driving parameters	Units	Scale factor
Pile diameter, D_{pile}	m	$\frac{1}{N}$
Pile impedance, Z	Ns/m	$\frac{1}{N^2}$
Impact hammer mass, m_{r}	kg	$\frac{1}{N^3}$
Mass drop velocity, v_{drop}	m/s	$\frac{1}{\sqrt{N}}$
Force on pile head, F_{p}	N	$\frac{1}{N^{2.5}}$

Table 1: Scaled quantities for 1G laboratory test

& Randolph is scaled down to a laboratory set up, using the scaling laws discussed above. The geometry and parameters of the laboratory test are shown in Table 2.

Parameter	Unit	Prototype	Scale model
Pile diameter, D	m	0.762	0.019
Pile impedance, Z	Ns/m	1750×10^3	1093
Impact hammer mass, m_{r}	kg	6860	0.107
Mass drop velocity, v_{drop}	m/s	3.27	0.517

Table 2: Parameters used in the numerical application for the prototype and the scaled model

Figures 4(a) and 4(b) present the force-time history and the corresponding frequency content of the force, computed at the pile head of the scaled model. Figure 4(a) show that the force at pile head of scaled model is 0.565 kN for a duration of impact of 0.5 ms. The latter value is equal to the scaled force factor $1/N^{2.5}$, and the scaled impact time factor of $1/N$, considering a scaling factor of 40. These correspond at the full-scale to a force of 5722.5 kN during an impact time of 20 ms. Moreover, Figure 4(b) show that the frequency content of the force is more than 5000 Hz which provides us insight on the sampling frequencies to be used in the envisioned in laboratory setup and how are these scaled, and hence a better understanding of the dynamic response of the pile-hammering system.

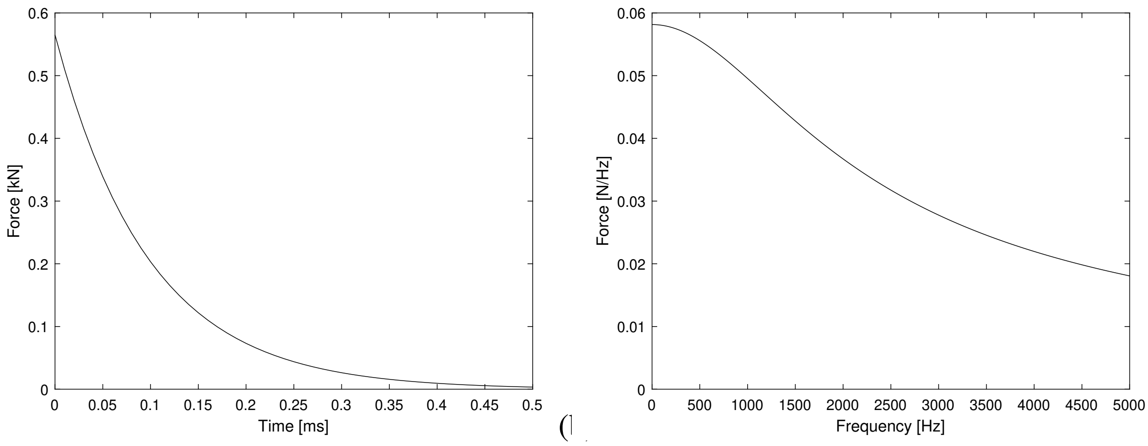
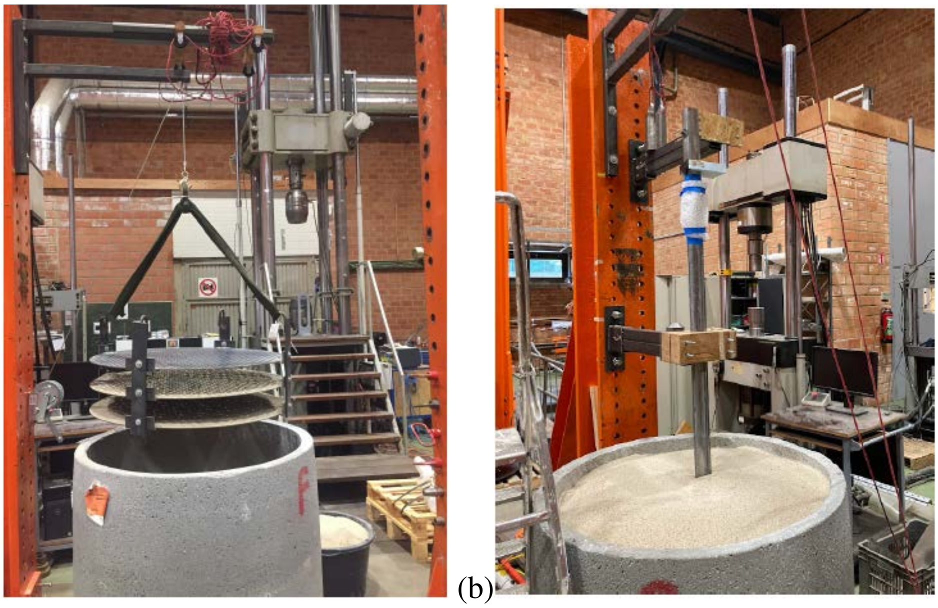


Figure 4: Variation of pile head response with (a) time and (b) frequency for the scaled impact hammering system.

3 EXPERIMENTAL INVESTIGATION

The envisioned laboratory setup is shown in Figure 1. It is based on the system initially developed by Holeyman [3], and has been used to drive tubular steel piles into rock masses [5]. The current set up consists of 10 kg drop weight (ram), which is attached to a rope and a pulley system, and a 0.6 kg anvil. A centering rod is fixed at the top of the hammer frame and ends inside the pile. Lateral supports to keep the pile vertical during the driving process are attached to the frame. The existing pile is a hollow steel cylinder of external diameter $D = 6\,\mathrm{cm}$, length $L = 50\,\mathrm{cm}$ and wall thickness $t = 6\,\mathrm{mm}$. A $1000\,g$ accelerometer is attached at a distance of $50\,\mathrm{mm}$ from the pile head. The pile is driven in a dry homogeneous sand of dry unit weight $\gamma_{\mathrm{dry}} = 1800\,\mathrm{kg/m^3}$, and relative density $D_r = 80\%$ that is representative of the soil conditions met in the North sea. The sand is placed in a concrete container of inner diameter $D_{\mathrm{box}} = 1\,\mathrm{m}$, inner height $H_{\mathrm{box}} = 1\,\mathrm{m}$ and thickness $t_{\mathrm{box}} = 5\,\mathrm{cm}$.

The relative density of sand was controlled using a sand pluviation system which is shown in Figure 5(a). This allows relatively homogeneous sand samples to be generated. The system is made up of three plates with holes with different diameters, namely 13 mm, 8 mm and 6 mm. Figure 5(b) shows the frame constructed which ensures the correct positioning of the pile during the installation process. Figure 6 shows a close up view of the location of the accelerometer, in preparation of a test.



(a) (b)

Figure 5: (a) Sand pluviation system (b) Positioning of the pile (hammered) to required depth.

Figure 6: Accelerometer positioned at 50 mm from pile head

4 CONCLUSIONS

This work presents a theoretical and an experimental attempt to study pile driving by impact hammering. For this purpose a numerical model has been developed, based on the seminal analytical work of Deeks and Randolph, as well as a small-scale well-controlled experimental set up for impact pile driving in a sand filled container. The numerical model includes a multi-body dynamic model to compute the force response on the pile head. Comparisons against the aforementioned analytical model validate the performance of the proposed approach. The numerical model can be then used to optimize the current laboratory setup by adding a cushion to the system and an absorbing membrane at the sides of the sand container to minimize wave reflections during the pile driving. In light of laboratory tests, scaling laws are discussed herein to help realistically scale down a prototype pile impact hammering system to a 1G laboratory model. Comparisons obtained in this study in terms of force-time response, between a prototype from the literature and a proposed scaled model, demonstrate the applicability of the scaling laws

Acknowledgements

Results presented in this paper were obtained within the frame of the project 3E220488 “Novel Installation and Extraction methods for Foundations of Offshore Wind Turbines” funded by the Global PhD partnerships (between KU Leuven and UCLouvain). The financial support is gratefully acknowledged. Furthermore, the authors highly appreciate the technical input and assistance provided by Eli Hamels and Pierre Mertens de Wilmars from the civil engineering laboratory at KU Leuven and UC Louvain, respectively..

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