Performance of the BLUE blow generator for centrifuge modelling at Delft University of Technology (DUT)

T.O. Quinten, C. Ioannou, M.A. Cabrera, A. Askarinejad, K.G. Gavin
Delft University of Technology, Delft, The Netherlands, T.O.Quinten@tudelft.nl, C.Ioannou-1@student.tudelft.nl, M.A.Cabrera@tudelft.nl, A.Askarinejad@tudelft.nl, K.G.Gavin@tudelft.nl

J. van Wijk
IQIP, Sliedrecht, The Netherlands, JortvanWijk@iqip.com

ABSTRACT: Generally, monopiles are installed dynamically by large hydraulic hammers. Although this method is reliable, tightening environmental regulations make it increasingly harder to operate this hardware without the need for sound mitigation measures. To safeguard the economic viability of offshore projects, the industry is seeking alternative ways of monopile installation. Impact prolongation is a promising method to reduce the environmental impact of pile installation. Several technologies have been proposed that leverage this principle. Due to the longer impulse duration, pile stresses change more gradually, leading to lower noise levels. Additionally, longer impulses may help reduce fatigue accumulation during installation by lowering the stress amplitude and reducing the number of stress cycles experienced. However, to facilitate industrial adoption, the foundation soil-structure interaction during installation and its implications on operational performance should be understood. Therefore, a small-scale blow generator for centrifuge testing is developed. This paper describes the observations from a test involving this actuator, executed at a g-level of 50g. The associated measurements focus on the blow impact dynamics, these include the duration, forces, and accelerations, as well as the pile frequency attenuation spectrum. The experiments are conducted in a water saturated GEBA sand sample, prepared at a relative density of 80%. This work contributes to the understanding of dynamic soil-structure interaction and its effect on pile behaviour, during and post-installation. Ultimately, this work should help facilitate the adoption of innovative installation technologies by the offshore industry.

1 INTRODUCTION

The rapid expansion of offshore wind energy as a clean power source has led to the widespread use of monopile foundations, which currently account for 80% of existing turbines (Wind Europe, 2019). Despite their efficiency, these foundations contribute significantly to the overall cost of windmill installations, constituting approximately 15% of the total expense. Consequently, there is a growing interest in comprehending the intricate soil-water-structure interaction dynamics during their installation process.

The predominant method of installation is impact driving, using large hydraulic hammers to drive the monopiles into the seabed. This form of dynamic installation is characterized by short, high amplitude force pulses resulting from the steel-to-steel collision between the ram and the pile. Consequently, the installation process is inherently noisy and leads to the accumulation of fatigue in the piles, as the driving stresses approach the yield limit.

The offshore wind industry's ambition to install increasingly larger turbines, necessitating larger foundations, is curbed by sound and environmental regulations, provided that the same installation methods are used (Duarte et al., 2021). Consequently, there is a need for new installation methods that facilitate the continued adoption of offshore wind energy. Among these, blow prolongation technology is a promising alternative to mitigate noise pollution (Koschinski & Lüdemann, 2020; Wagenknecht, 2021). This paper showcases the performance of the prolonged blow generator developed at Delft University of Technology and based on experimental data from a series of centrifuge experiments on water saturated GEBA sand samples.

2 METHODS

Experiments are performed in the centrifuge facility at Delft University of Technology (DUT). The centrifuge of DUT is a beam-type centrifuge with a diameter of 2.4 m. The capacity is 9000 kgF, equivalent to a 30 kg payload at 300g. The usable volume of the carrier measures 560 x 350 x 210 mm (H x W x D), as illustrated in Figure 1. For further details on the centrifuge facility, the reader is referred to the work of Allersma (1994).

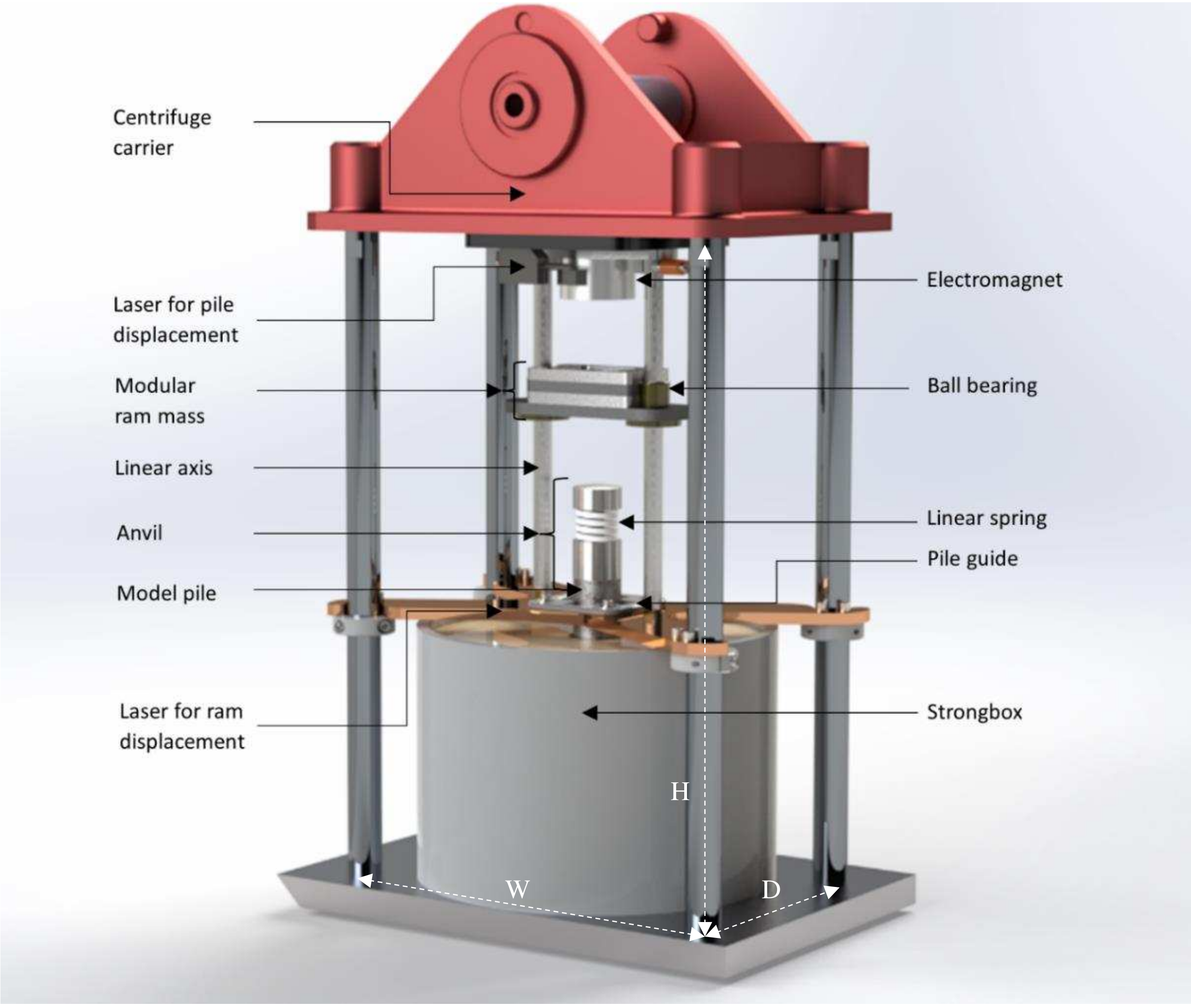


Figure 1. Annotated render of prolonged blow actuator of DUT, shown assembled inside the centrifuge carrier. Adapted from Quinten et al. (2022).

Experiments utilize the prolonged blow generator of DUT, a purposefully developed piece of centrifuge hardware for the geotechnical centrifuge at DUT, as depicted in Figure 1. This device is a single-acting hammer, that employs a linearly guided modular ram mass to drive a tubular pile. An anvil is placed on top of the pile and consists of three components: (i) a top cap, this is the part that is impacted by the ram; (ii) a stiff linear spring, and (iii) a base that partially slides into the pile cavity and simultaneously confines the spring bottom-end. The top cap has a protruding rod that extends downward, first through the spring and subsequently through the anvil's base. A nut prestresses the spring, ensuring contact between the components during impact.

The linear spring embedded in the anvil is configured to prolong the duration of the impact by more than one order of magnitude with respect to impact hammering. Due to the incorporation of this spring, the interface stiffness is reduced, which results in a characteristic long, low-amplitude blow. Further details on the functionality of this system are provided in Quinten et al. (2022).

The experiments presented in this work employ a ram mass of 1.889 kg (model scale). The model pile has the following properties: (i) diameter, $D_P = 42$ mm; (ii) wall thickness, $t_P = 2$ mm, and (iii) length, $L_P = 175$ mm. The sample consists of water saturated GEBA sand at $D_r = 80\%$. A summary of the model parameters is given in Table 1.

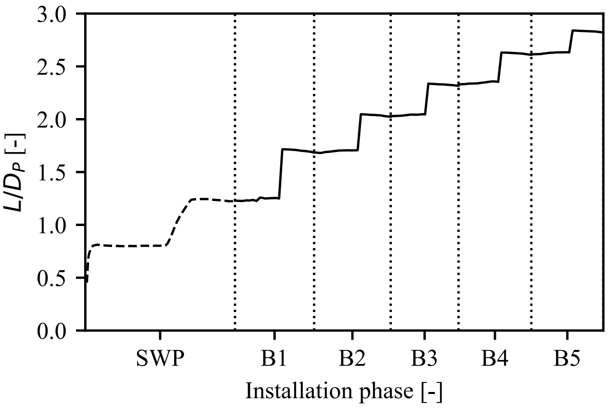


Figure 2. Normalized cumulative pile displacement as a function for the SWP-phase for five consecutive blows (B1 to B5). Vertical dashed lines demarcate the transition from one installation phase to the next.

The model pile is equipped with an axial load cell that records the exerted force 20 mm from the pile head. The load cell consists of four strain gauges wired in a full Wheatstone bridge configuration, allowing for the computation of pile head force based on the localized strain.

The test protocol starts with a self-weight penetration (SWP) phase, where the pile is allowed to settle freely under its self-weight and the ram's weight, first at 1g and subsequently and 50g (N = 50). Following the SWP phase, a series of single blow events at 50g are conducted, driving the pile up to a depth of approximately $3D_P$.

Between blows, the centrifuge is intermittently halted and restarted to manually reset the hammer height for the subsequent impact. This procedure is necessary due to a design shortcoming that prevents resetting the hammer during flight. Each pause lasts approximately 5 minutes (excluding the time required to halt and restart the centrifuge). Intermittently halting the centrifuge is likely to have a minor effect on the overall results, as the post-blow stress state is not preserved between experiments. Upon reinitiation of the experiment, only the global stress state is recovered, while the nuances due to installation effects are lost.

Table 1. Summary of Model parameters for the centrifuge experiments.

Model parameter	Value	Unit
Centrifuge acceleration	50	[g]
Ram mass	1.889	[kg]
Falling height	40	[mm]
Pile diameter, D_P	42	[mm]
Shaft thickness, t_P	2	[mm]
Pile length, L_P	175	[mm]
Relative density, D_r	80	[%]

3 RESULTS

Figure 2 shows the pile displacement accumulated over the SWP and a sequence of 5 blows (B1 to B5). Dotted lines demarcate individual installation phases. The displacement realized during the SWP phase of the experiment is shown by the dashed line. The double stepped shape originates from the fact that the SWP-phase consists of a 1g (initial offset on y-axis) and a Ng part (embedment increment from $0.75D_P$ to $1.25\ D_P$). In total the pile settles approximately $1.25D_P$ (≈50 mm) under the combined influence of its self-weight and the ram mass.

For the subsequent five blows, it is observed that the penetration per blow decreases as the pile embedment increases. The latter follows logically from the increasing soil resistance at larger embedment depth, as the potential energy of the ram is virtually constant over the whole installation sequence.

Visually, the stepwise installation profile bears resemblance to the installation profiles obtained during impact hammering, as shown in the work of Van Zeben et al. (2018). Due to the relatively large driving energy, the increments for prolonged blow installation are fewer and of a significantly larger magnitude compared to impact driving. While not visually evident, the mode of installation shifts from stress-wave-driven during impact driving to rigid body motion, primarily due to the prolonged impact duration. Therefore, the installation mode can be described as quasi-dynamic, falling between impact driving and cyclic jacking.

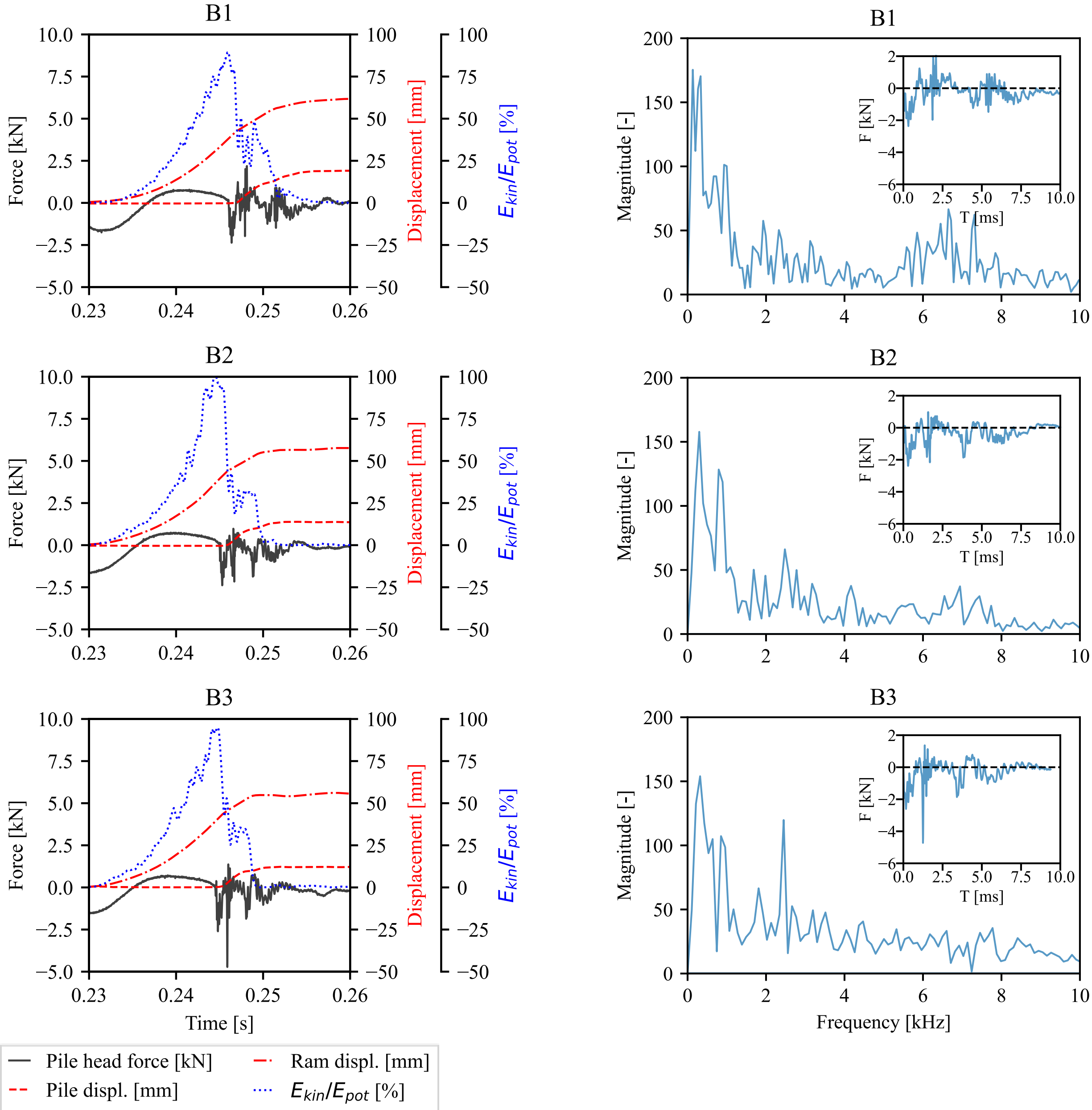
3.1 Pile displacement, ram displacement, driving force and ram energy conversion

Figure 3 (a) shows the pile displacement (dashed line), ram displacement (dash-dotted line), axial load cell (LC) signal (solid line) and the efficency of the conversion of potential to kinetic engery (dotted line) for blows B1 to B3 of the pile installation sequence. This data was recorded at a sampling rate of 100 kHz.

Upon release of the ram mass, it is observed that the ram displacement increases. Simultaneously, a sinusoidal-shaped signal is recorded by the LC. It is believed that this is an artifact resulting from electromagnetic (EM) noise emitted during the ram's release. The moment of impact coincides with the inflection point of the ram displacement chart. At this point, the momentum transfer between the ram and the pile initiates. Concurrently, the LC registers an increase in the pile head force and the pile starts to move. By differentiation, it is possible to back-calculate the ram mass impact velocity. From these analyses it is determined that on average 95% of the potential ram energy is converted into kinetic energy, as shown by the blue dotted lines in Figure 3 (a).

From the high-speed data in Figure 3 (a), it is evident that the pile displacement is not instantaneous (Figure 2), but gradually increases over approximately 10 ms. Pile movement seizes when the major oscillations in the LC signal have subsided. For all three blows shown in Figure 3, this is approximately 10 ms after the first contact between the ram and the pile. At prototype scale, this represents a blow duration of roughly 500 ms, compared to 4-8 ms for impact hammering (Winkes, 2018).

The maximum pile head force varies between 2.5 and 5 kN. It is likely that the exact maxima are not captured in all instances, even at a sampling rate of 100 kHz, resulting in this mutual fluctuation. Compared to impact driving, it is concluded that blow duration is increased while the peak head force is reduced, as intended.



(a) Pile displacement (dashed line), ram displacement (dashed-dotted line), pile head force (solid line) and efficiency of potential to kinetic energy conversion (dotted line) as a function of model time.

(b) Frequency attenuation spectra. Inner plots depict the force signals used for the FFT analyses. The latter are recorded by an axial load cell placed 20 mm from the pile head. Only the portions of LC data where pile movement is observed are used for the analyses.

Figure 3. High frequency (100 kHz) experimental data, recorded during the first three blows (B1 to B3) of the installation sequence of the model pile. All measurements are at model scale.

3.2 Pile attenuation spectra

Figure 3 (b) shows the frequency attenuation spectra of the pile corresponding to blows B1 to B3, as obtained from the Fast Fourier Transform (FFT) analysis on the LC measurements. The underlying LC data is shown in the insert plots of Figure 3 (b) and corresponds to the portion of data recorded while the pile is moving (Figure 3 (a)).

Peak frequencies are consistently found in the 0 to 1, 2 to 3, and 6 to 8 kHz bandwidths, while their magnitude decreases consistently with increasing frequency. Generally, the frequency spectrum is dominated by relatively low frequency oscillations. This is in line with the pile's long excitation time, causing a shift towards the lower end of the frequency spectrum when compared to impact hammering.

A limited shift in frequency content from the 0 to 1 kHz frequency band towards higher excitation frequencies is observed during consecutive blows. Consequently, the increase in subsoil stiffness appears to have a minor effect on the overall pile response. This could stem from the pile's relatively shallow embedment depth or a temporary decrease in soil stiffness, potentially caused by the generation of excess pore pressures. Further experiments are underway to collect the necessary data to support these hypotheses.

4. CONCLUSIONS

Blow prolongation offers a promising alternative to conventional pile installation techniques, particularly as the offshore wind industry seeks methods to install increasingly larger (monopile) foundations while mitigating impact on marine life. This paper presents results from a dynamic installation sequence of a 42 mm model pile driven into a water saturated GEBA sample using the DUT prolonged blow generator.

Although fewer and larger displacement increments per blow are recorded, the installation profile of the model pile resembles that of an impact-driven pile. Analysis of the LC data for blows B1 to B3 reveals a blow duration of approximately 1 ms. At prototype scale, this equals an impact duration of 500 ms, representing 60-120 times increase compared to impact hammering. Pile movement is also recorded within the same time interval. Back-analysis of the ram displacement data shows that 95% of the ram's potential energy is converted into kinetic energy.

Pile attenuation diagrams are constructed for blows B1 to B3. It is observed that the spectra largely coincide between blows, indicating consistent driving conditions. As expected, lower frequency (< 2 kHz) oscillations are best represented within the spectrum. Due to the limited change in frequency content towards higher excitation frequencies for higher blow numbers, the influence of a stiffer soil response appears to be limited. This may be due to the relatively shallow pile embedment (1.25 to 2.25 L/D_P) or the generation of excess pore pressure, effectively softening the soil reaction. Further centrifuge tests are ongoing to substantiate these hypotheses.

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