

Experimental investigation of vibratory extraction of monopiles for offshore wind turbines using 1g models

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ABSTRACT: As first offshore wind farms approach the end of their operational life, there is a pressing need for timely decommissioning, with particular emphasis on the critical importance of extracting their foundations. Most offshore wind turbines are supported by monopiles that can weigh up to 2000 tons. Currently, industry practice involves cutting the pile at the seabed, leaving the remainder embedded in the soil. Fully decommissioning monopiles poses significant engineering challenges in the harsh offshore conditions but it will offer the potential to minimize ecological and financial impacts associated with offshore wind energy. One promising solution is the use of vibratory hammers, like those for installation, which can substantially reduce the uplift force required for extraction. Such technique can reduce underwater noise, minimize environmental impact, and improve efficiency by facilitating quicker and less disruptive operations. Given the limited guidance and understanding of the soil-monopile interaction mechanisms during extraction, this work explores these processes through a series of 1g laboratory experiments in dry North Sea sand. For this purpose, a scaled miniature vibratory hammer was developed and employed to evaluate the effectiveness of vibration-assisted scaled monopile extraction. Results demonstrate that vibration can significantly lower the extraction force and highlight the need for further investigation to identify the key parameters for optimizing the decommissioning process. These findings will inform future numerical studies and validate results through centrifuge testing.

KEYWORDS: offshore geotechnics, offshore wind turbine foundations, decommissioning of monopiles, monopile vibratory extraction, 1g lab tests.

1 INTRODUCTION

Offshore wind energy plays an increasingly vital role in meeting Europe's electricity demands. At the North Sea Summit II in 2023, nine countries committed to increasing production capacity from the current 32 GW to 300 GW by 2050 (European Commission, 2020). In addition, the first wind farms, installed in the early 2000s, are now approaching the end of their planned 25-year lifespan (Shafiee, et al., 2016), raising the issue of decommissioning.

The dismantling of foundations represents the most significant cost, and uncertain soil conditions pose additional risks (Yilmaz, et al., Dec. 2023). Currently, monopiles account for more than 80% of offshore wind turbine foundations (Byrne & Houlsby, 2003), due to their simple design and well-established supply chains (Gupta & Basu, 2020). The current decommissioning method is cutting the monopile at seabed level (Hinzmann, et al., 2017). However, this approach has major drawbacks: a substantial amount of buried steel (tens of thousands of tons per wind farms) remains in place, it complicates the future installation of larger piles at the same strategic locations and it is a risky operation due to the confined space, the water depth and the blindness of the process (Hinzmann, et al., 2018).

Several extraction techniques are under consideration, with vibro-extraction (Jiang, 2021) (which transmits vertical vibrations to the pile to reduce soil resistance and facilitate removal) being the most promising. However, predictive models for this method remain empirical and the sector is still in its early stages of development. An exception is the innovative work of Davidson *et al.* (2017) concerned with oil and gas piles removal with vertical vibrations with large reduction in necessary extraction force. Other approaches, such as hydraulic extraction (Hinzmann, et al., 2020) and vibro-

jetting (GMBWorks, 2023), are still at the prototype stage, and foundation removal methods remain largely unexplored (Nielsen, 2022).

This research studies the potential of vertically vibrating the pile to reduce the pulling force necessary for the fully decommission monopiles of the offshore wind turbines via a small-scale modelling.

2 EXPERIMENTAL SETUP

2.1 Vibro-driver and Pull-out apparatus

To compare pile extraction with and without vibrations, the extraction force was selected as the primary parameter for comparison. A stepper motor with velocity control is used to apply the extraction force, ensuring a controlled process during the whole decommissioning. The motor winds a rope that passes through pulleys and is connected to the top of the pile with a screw. Extraction force was continuously recorded using a force sensor mounted on the rope near the pile head. The experimental setup is illustrated in Figure 1.

The motor extracted the pile at a constant velocity of 16.75 cm/min. This velocity was verified using displacement measurements obtained from a camera, with image analysis conducted using OpenCV (OpenCV, 2025). Displacement was calculated as the change in position between a color marker placed on the pile and a laser as a fixed marker (a reference point). The variability in measured velocity across different tests was less than 0.1%.

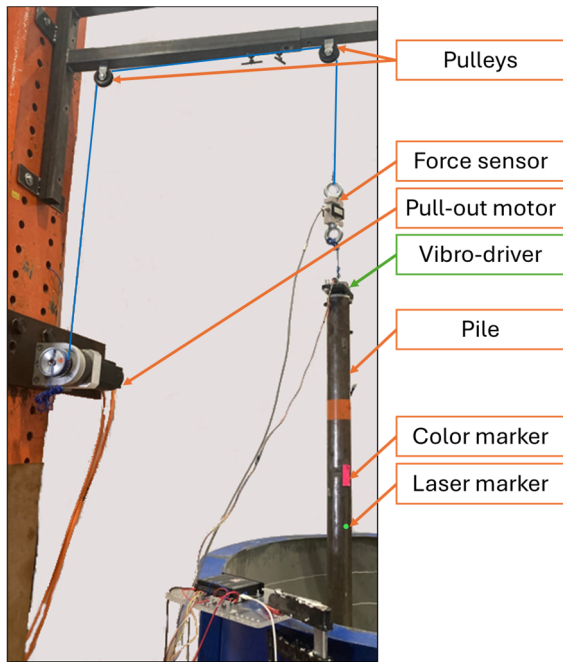


Figure 1. Test setup in the laboratory.

The vibro-driver used is a small scale vibro-hammer previously developed for installation studies (Simonin, et al., 2024) (Simonin, et al., 2025). It consists of two eccentric masses rotating in opposite directions via a gear system. The resulting force creates vertical vibrations. The vibro-hammer is shown on Figure 2.

Piles were installed with a small-scale impact hammer, described in (Deckers & Defer, 2022-2023). A mass of 1.2kg with a drop-height of 30cm, a wood cushion, and an anvil placed on the top of the pile were used. The pile embedment ratio for all experiments is five diameters (i.e. 30cm), which was reached after 100 ± 10 impacts for all installation, showing an adequate repeatability across the tests.

2.2 Scaling laws

The scaling laws are based on the conservation of key variables, in this case, the gravity was chosen. The length factor, λ_L , is defined by:

$$\lambda_L = \frac{L_p}{L_m} = \frac{1}{N} \quad (1)$$

where L designates a length, and the subscripts p and m the prototype and the model respectively. All scaling laws were derived based on the scaling factor N , set to $N = 70$. Table 1 presents the dimensions for the small-scale model as well as the equivalent prototype. While the prototype diameter corresponds to a typical value of early offshore wind farms, the length and weight are slightly larger than those of a standard monopile used in the North Sea (Negro, et al., 2017).

The scaled-up version of the vibro-driver model used in this preliminary study does not exactly correspond to commercial devices, as it has a smaller eccentric mass and a higher operating frequency. Nevertheless, the generated forces (up to 30,000kN) fall within the feasible range for field equipment, given that the largest commercial vibro-hammers can reach 40,000 kN at a frequency of 23 Hz with an eccentric moment of 2000 kgm (Dieseko group, 2025) (Cape Holland, 2025). In contrast, scaling of the impact hammer is realistic, as prototypes of comparable dimensions are available (IQIP, 2025).

Table 1. Specifications of the experiments.

	Parameter	Model	Scaling	Prototype
Pile	Diameter, D [m]	0.06	$1/N$	4.2
	Thickness, t [m]	0.0014	$1/N$	0.098
	Length, L [m]	1.35	$1/N$	94.5
	Mass, m_p [kg]	2.8	$1/N^3$	944,000
Impact hammer	Drop height, h [m]	0.3	$1/N$	21
	Ram mass, m_r [kg]	1.2	$1/N^3$	411,600
	Eccentric masses, m_e [kg m]	$8e^{-6}$	$1/N^4$	192
Vibro-hammer	Mass, m_v [kg]	0.32	$1/N^3$	109,760
	Frequency, f [Hz]	350-525	\sqrt{N}	42-63

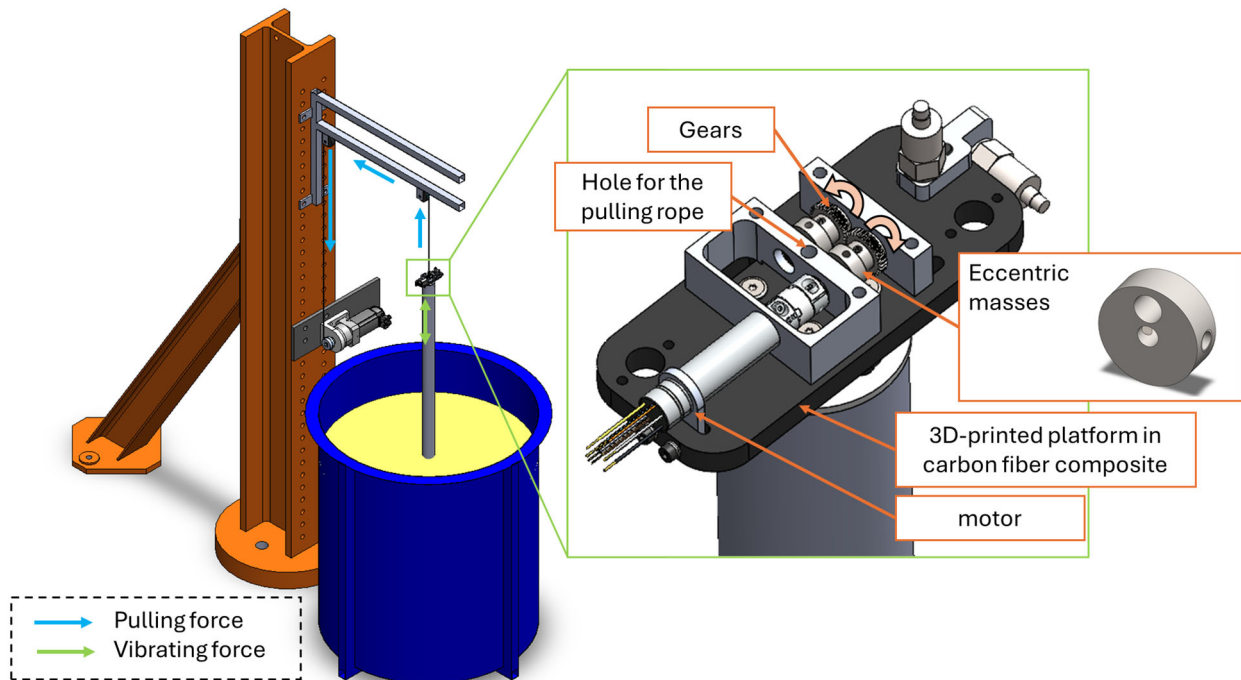


Figure 2. Schematic of the mini-vibro-extractor.

The model pile with the vibro-hammer and the clamping parts weights 30.5N while the dynamic force generated by the vibro-hammer ranges from 38.7N to 87N.

2.3 Soil sample

The soil sample, contained in a purposely-built steel tank (Deckers & Defer, 2022-2023), is a cylinder of 1110mm for a 1250mm height. The soil employed for the tests was dry North Sea sand which characteristics are given in Table 2.

Table 2. North Sea sand properties.

Parameter	Symbol	Value	Unit
Median particle size	d_{50}	0.2	mm
Maximum dry unit weight	$\gamma_{d,max}$	17.9	kN/m ³
Minimum dry unit weight	$\gamma_{d,min}$	15.2	kN/m ³

The sand was initially pluviated in a loose state in the tank. The target density was then achieved by densifying the sand with a vibrating needle in a systematic pattern, providing a consistent and reproducible preparation method across experiments. The average density achieved is $37 \pm 3\%$.

Cone tip resistance was measured before each test using a miniature cone penetrometer (1 cm² area, 60° cone angle). Figure 3 shows the average cone resistance profile and the corresponding standard deviation across the tests. This demonstrates the quality and the repeatability of the preparation method.

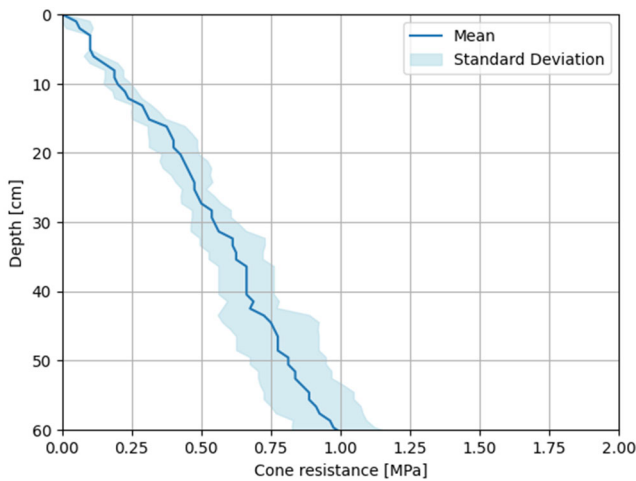


Figure 3. Cone penetration tests at the future positions of the pile.

3 PRELIMINARY RESULTS AND DISCUSSION

This study explored the influence of the vibration frequency for a constant eccentric moment (8g.mm) on the pull-out force necessary to extract the model pile. The forces measured for the different frequencies of the vibro-driver are presented in Figure 4. Time $t=0$ corresponds to the moment when the pull-out motor is activated; however, for tests involving vibration, the vibro-hammer was already running prior to this time in order to reach the target operating velocity before extraction began. In these cases, the vibro-driver started between 10 and 20 seconds before the start of force data recording.

A first observation is that all curves converge to the weight of the pile, indicating complete decommissioning. The pink curve ($f = 0$ Hz) represents the force required without any applied vibration. During this test, the vibro-hammer was removed from the pile, which explains why the curve reaches a lower force than the others: the motor did not have to carry the additional weight of the vibro-driver.

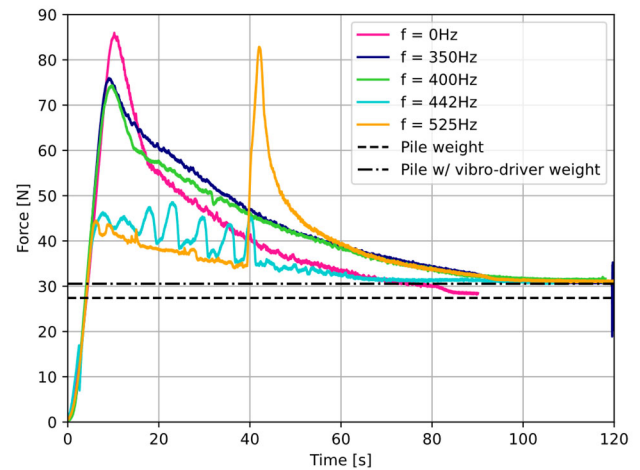


Figure 4. Pull out force during the pile extraction at different frequencies.

The main observation from Figure 4 is that vibration reduces the initial resistance of the pile. The results indicate that higher vibration frequencies generally lead to lower extraction forces. However, the four tested frequencies separate into two distinct regimes: the lower frequencies (350 Hz and 400 Hz) produce only a modest reduction in extraction force, whereas the higher frequencies (442 Hz and 525 Hz) achieve a much greater reduction, with little difference between them despite the large frequency gap. At 442 Hz and 525 Hz, the peak extraction force is approximately 45 N for a pile weighing 30 N, compared to 85 N without vibration. This corresponds to a decrease in the friction component from roughly 55 N to about 15 N—more than a threefold reduction. It aligns with the findings of Davidson *et al.* (2017), on scaled 1 g experiments: pull-out loads under vibration were reduced to the pile’s self-weight in loose sand ($Dr = 17\%$), while they observed a 36% reduction in dense sand ($Dr = 77\%$). In this study, since the relative density lies between the two examined densities by Davidson *et al.* (2017) they examined, the observed 70% reduction in extraction force aligns with their database and complements it. Further testing in the intermediate range between 400 Hz and 442 Hz is needed to determine whether the transition between these regimes occurs gradually or abruptly.

For the test at 525 Hz, a force peak appears around 42 seconds. This occurred because the vibro-hammer was switched off at that moment. To investigate this phenomenon, an additional test was conducted in which the vibro-driver operated for around 45 seconds before being stopped, after which the extraction process began. As shown in Figure 5, the required extraction force in this test was significantly higher than in the test without vibration. This observation suggests that stopping the vibration prior to full extraction may increase the resistance of the pile. This could be due to a densification around the pile in this loose sand medium.

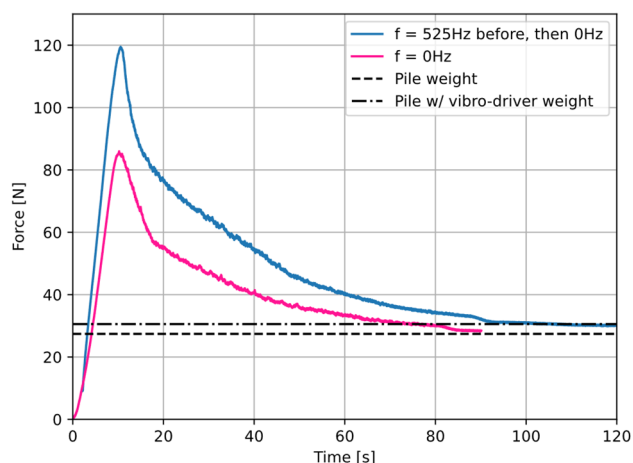


Figure 5. Comparison between simple extraction and vibration for 45 seconds then extraction.

4 CONCLUSION

The tests performed in loose dry sand demonstrated that the use of a vibratory hammer can reduce the force required for complete pile extraction by 70%. Vibratory extraction thus appears as a powerful tool for the improvement of the life cycle of offshore wind farms, with a potential to decrease the waste of steel and complex underwater operations.

This study highlights the importance of further research on vibratory decommissioning techniques. These preliminary results indicate a trend in which higher vibration frequencies correspond to lower extraction forces. However, it remains to be investigated if higher frequencies can reduce further the extraction force or if there exists an optimal frequency range for effective decommissioning. Future investigations should examine not only the influence of frequency but also the role of eccentric moments, in order to determine whether frequency alone or the resulting vibratory force is the governing parameter. Additionally, the duration of vibration warrants further study to assess whether initial vibration is sufficient for effective decommissioning, or if continuous vibration is necessary throughout the entire extraction process. Furthermore, tests should be conducted in higher sand densities and saturated conditions for greater representativeness.

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