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Vibratory extraction of piles in sand: insights of a small-scale 1g investigation on the influence of vibratory force

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ABSTRACT: As early offshore wind farms reach the end of their operational lives, the issue of the decommissioning of the offshore wind turbine is raising. The decommissioning of monopiles, the most widely used foundation type for bottom-founded turbines, presents critical environmental and engineering challenges. The planned practice of cutting piles at seabed level risks leaving millions of tonnes of steel embedded in the seabed, raising concerns regarding long-term environmental impact and potential loss of resource value. This study investigates an alternative decommissioning strategy: full monopile extraction using vibratory methods. By applying vertical vibrations to reduce shaft friction, vibratory extraction may enable the complete recovery of embedded piles, supporting more sustainable and circular decommissioning practices. We present the design and scaling of a 1g experimental set-up developed to simulate this process, along with a parametric study assessing the influence of vibratory force on extraction performance. The vibratory force varies via the eccentric moment at a representative vibration frequency. Results provide insight into the relationship between vibratory force amplitude and frictional resistance, offering preliminary guidelines for upscaling and industrial implementation. These findings support the integration of vibratory tools into future decommissioning strategies, contributing to enhanced life-cycle sustainability of offshore wind infrastructure.

1 INTRODUCTION

As the lifespan of an offshore wind turbine is about 25 years, many of the earliest wind farms are approaching their end of life. Decommissioning of the offshore wind foundations, which are mainly monopiles (Byrne and Houlsby, 2003), is currently performed by cutting them a few meters below the seabed and leaving the embedded part in situ. Although this approach is commonly adopted in the oil and gas industry, it presents several drawbacks. In particular, it prevents the full recovery and recycling of the steel that is embedded. In addition, leaving buried foundations in place restricts access to valuable sites for repowering and may pose hazards to fishing activities and marine industries (Hinzmann et al., 2018). It is not feasible to extract the monopiles in their entirety by means of a pull-out manoeuvre, since the lifting capacity of the vessel's crane is inadequate for the task.

To address these challenges, several techniques are currently under investigation to reduce the force required for foundation extraction. While these methods remain at an early stage of development, firsts studies have demonstrated that vibro-extraction is a promising solution for reducing friction forces (Davidson et al., 2017).

This study investigates the influence of frequency and eccentric mass on extraction efficiency to determine the most effective operational parameters.

2 EXPERIMENTAL SETUP

A *60mm* diameter pile was used, scaling down a full-scale *6m* diameter pile by a factor of 100. Figure 1 illustrates the 1g test conditions.

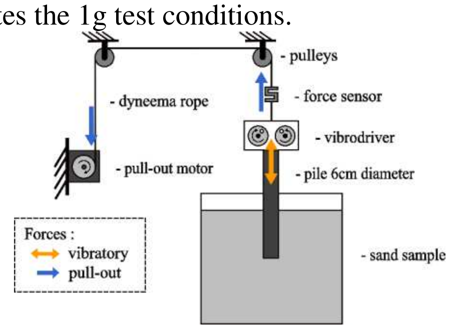

Figure 1. Schematics of the experimental setup.

2.1 Pull-out system

The pulling action of a crane is replicated by a stepper motor winding a rope through a system of pulleys. The extraction force is measured using a force sensor positioned close to the vibrodriver.

2.2 Vibrodriver

A new small-scale vibrodriver prototype was developed, based on a previous design for geo-centrifuge testing (Simonin et al., 2025). An electric motor drives counter-rotating eccentric masses, cylindrical elements with off-centre holes, through a gear system. Accelerometers are mounted on the vibrodriver to verify correct operation and monitor the generated vibrations.

Scaling of the vibrodriver at 1g for this system has led to the use of larger eccentric masses (4 g.mm to 64g.mm) at frequencies in the range [50 Hz, 500 Hz].

2.3 Sand sample

The soil sample consists of dry North Sea sand contained within a steel cylinder with a diameter of 1100 mm and a height of 1250 mm.

The sample is prepared using a combined method of dry pluviation and a vibrating needle applied in a systematic pattern. To ensure repeatability of the soil preparation, cone tip resistance measurements are performed prior to each test using a miniature cone penetrometer (1 cm^2 and 60° cone angle).

3 RESULTS AND CONCLUSIONS

Figure 2 shows the dimensionless friction force, normalised by the average pull-out force, as a function of the pile extraction ratio for different vibration frequencies. The results indicate that vertical vibrations reduce the required initial pull-out force. However, a sufficiently high vibration frequency (here, $f \geq 442$ Hz) is necessary to achieve a fourfold reduction in the pull-out force throughout the entire extraction process.

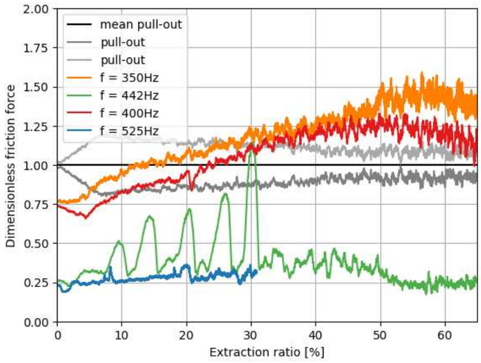

Figure 2. Extraction force in dry sand samples (DR=37%).

Further investigations are required at different scales and under geo-centrifuge conditions in order to extend these findings and provide reliable guidance for full-scale applications. Exploring the influence of parameters such as eccentric mass, frequency, sand density and extraction velocity could offer valuable insights for optimizing the technique.

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