Physical modelling of offshore infrastructure

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ABSTRACT: Physical modelling underpins and has supported our understanding of offshore infrastructure development around the globe. Offshore wind is now an established industry that has benefitted from immense research efforts. Rapid expansion of the offshore wind industry, and the sheer scale of the infrastructure required to meet targets, place sustainability in the spotlight and incentivise innovation as well as increased efficiencies in design and processes. As the offshore wind industry moves to new regions with different seabed soil conditions, understanding of these natural soils and their response in the complex soil-structure interaction problems that characterise foundations and anchors for offshore wind turbines increasingly comes into focus. With this comes opportunities for significant advances ranging from site investigations and across the life cycle of the foundations.

1 INTRODUCTION

Physical modelling remains an important methodology, and has supported offshore infrastructure around the globe. The impact of geotechnical research, with a heavy reliance on physical modelling, on the offshore industry in Australia has been documented in Randolph et al. (2021).

A range of physical modelling approaches, from small scale testing on the laboratory floor and in the centrifuge, as well as medium to large scale testing in the laboratory, in the field onshore and offshore have all contributed to better understand soil-structure interaction and to de-risk specific challenges associated with offshore infrastructure.

Offshore wind is now an established industry that has benefitted from immense research efforts. A large part of this effort has relied on commercially available soils to better understand the complex soil-structure interaction problems that characterise foundations and anchors for offshore wind turbines. As the offshore wind industry moves to new regions with different seabed soil conditions, understanding of these natural soils and their response in soil-structure interaction increasingly comes into focus. Even in established regions, the offshore wind industry continues to evolve, shining a spotlight on opportunities for significant advances ranging from site investigation and across the life cycle of the foundations.

Physical modelling (of offshore infrastructure) has, of course, benefitted significantly from advancements in equipment and measuring techniques. This is covered in a separate keynote at this conference (Blanc 2024).

This paper selects a small number of examples, highlighting innovation in physical modelling to address challenges related to offshore wind energy infrastructure. Applications range from (vibro-driven) pile installation to suction bucket response, with the underlying thread of careful consideration of the soil conditions targeted for testing.

2 PILE INSTALLATION

2.1 Vibro-driven piles

Vibro-driving is increasingly being considered for pile installation offshore, driven by significantly reduced acoustic emissions compared to impact-driven pile installation, fast installation times and mitigation of pile run as the pile and vibro-driver are connected to the crane (see Figure 1). Like impact-driving, vibro-driving is a dynamic installation method. In contrast to impact driving with its intermittent percussive signature, vibro-driving transfers continuous vertical vibrations from the vibro-driver to the pile, typically at a frequency of around 23 Hz. The vibrations are generated by pairs of eccentric counter-rotating masses in the vibro-driver. The crane is decoupled from this excitation through the upper part of the vibro-driver, the suppressor housing. Vibro-driver and pile are connected by multiple clamps. This arrangement also allows the pile to be upended and positioned, i.e. not requiring a separate tool for lifting.

Figure 1. Vibro-driven monopile installation (source: Cape Holland).

Significant experience exists using vibro-driven installation for piles onshore, often sheet piles (e.g. Viking 2002, Massarsch et al. 2021). Experience with large diameter cylindrical piles (monopiles) offshore is limited (e.g. Doherty et al. 2015, Holeyman et al. 2020 and the recently constructed Kaskasi offshore wind farm) but set to rapidly expand with vibro-piling being considered for multiple offshore wind farm installations. To enable vibro-installation of monopiles, ever larger vibro-drivers are being commissioned.

Vibro-driving is known to work well in sand, with friction fatigue (Heerema 1980, Moriyasu et al. 2018), dynamic effects (Whenham and Holeyman 2012; Massarsch et al. 2017) and in saturated sand also excess pore pressures identified to contribute to successful vibro-driving. However, details of the mechanisms governing vibro-driving remain to be better understood.

The prospect of vibro-driving being used to install large numbers of monopiles offshore has prompted significant research recently, much of which is underpinned by physical modelling, either in the form of field testing (e.g. Achmus et al. 2020, Tsetas et al. 2023), medium (e.g. Fischer and Stein 2022) or small scale (e.g. Remspecher et al. 2019, Vogelsang et al. 2017) physical modelling.

Combining the advantages of small scale testing under controlled conditions with relevance of measured data to the field through similitude of stress conditions and established scaling laws, centrifuge testing of vibro-driven piles has been enabled through the development of a mini vibro-driver (Hein Mazutti et al. 2024a) and associated apparatus to also allow (cyclic) lateral loading post pile installation without the need to stop the centrifuge. Figure 2 shows a vibro-driven pile installation being performed in the National Geotechnical Centrifuge Facility (NGCF) at the University of Western Australia, requiring simultaneous control of the vibro-driver which is achieved through bespoke in-house software and the actuator that follows the pile down via a feedback loop as the pile penetrates into the soil. This guiding through a linear rail ensures vertical pile penetration despite weight of the sensor cabling between the pile head and the centrifuge arm (with the centre of gravity of the apparatus as such aligned with the pile central axis).

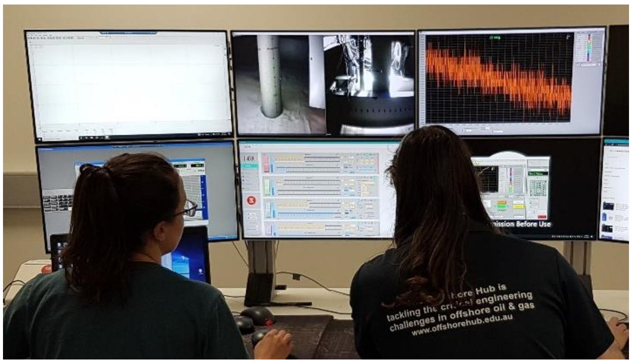

Figure 2. Vibro-driven pile installation in the centrifuge at UWA.

The instrumentation (including a photosensor measuring the rotational speed of the undulated wheel that generates the vibrations, a linear Hall effect sensor to measure the displacement of the vibrating mass, an oscilloscope, an accelerometer and four optic fibres positioned along the pile shaft) allows data of the applied vibrations and resulting pile response to be measured. Initial results have been reported in Hein Mazutti et al. (2022a, b and Bienen et al. 2023a). Results from multiple series of centrifuge testing of pile installation into dry and saturated sand of different relative densities are discussed in Hein Mazutti et al. (2024b), probing the roles of vibration frequency and applied dynamic force in relation to the static force. These physical modelling results provide a significant database in themselves, for validation of numerical models and vibro-driving prediction methods (El Haffar et al. 2023), but further value can be gained by collaboratively connecting databases with evidence obtained through different (physical modelling) approaches as is the intention.

The vibro-driven pile tests performed in the centrifuge were carried out in multiple samples of ‘UWA superfine silica sand’. Commercially available soils such as this clean sand enable general research. They are available in quantities required for centrifuge testing over a long period of time and tend to be well characterised which facilitates numerical modelling as well.

However, physical modelling may also be required in soils representative of seabed soil conditions in a region or even at a specific site to understand additional complexities and ensure relevance to field conditions, especially as offshore wind moves into new regions with different seabed soil conditions and limited experience.

2.2 Pile installation in complex soil conditions

One such new region with significant planned offshore wind development but limited pile installation experience is off the East coast of the USA, which has prompted large scale research into glauconitic soils (e.g. DeGroot 2023, Westgate et al. 2023). Another is off Taiwan, where multiple pile run incidents have been reported (e.g. upstreamonline 2022).

In Australia, experience from offshore energy developments on the North West Shelf has heightened awareness among the (offshore) geo professions of challenges during pile installation into cemented carbonate soils, which at the time required remediation costing hundreds of millions of dollars. Differences in behaviour between silica and carbonate sand can be profound, with significantly higher compressibility and particle breakage at lower stresses evident in the latter (e.g. Erbrich et al. 2010, Watson et al. 2019). New collaborative research with industry explores the effects of these differences on pile response under cyclic lateral loading and changes in soil state arising from the installation process of large diameter thin-walled cylindrical piles in uncemented carbonate sand.

Seabeds in areas earmarked for offshore wind development may include variably cemented carbonate soils. The potential for damage to the pile during impact-driven installation into cemented sand has been shown in Nietiedt et al. (2020), with Nietiedt et al. (2023) providing a framework to assess the potential for pile damage and extrusion buckling in sand.

Figure 3. Pile installation in variably cemented carbonate sand.

Ongoing research investigates impact-driven cylindrical piles in cemented sand through field tests: Figure 3 shows a pile being installed by impact-driving, with a number of other piles of varying dimensions having been installed prior, and capacity testing undertaken as shown in Figure 4.

The onshore test site near Perth was selected as the soil conditions, including geological history and degree of cementation, are relevant to sites in Western Australia that may be considered for development of offshore wind farms. Analysis of the data of this first testing campaign and further testing are ongoing.

Figure 4. Pile capacity testing in variably cemented carbonate sand.

In contrast to soils offshore, the soil at this site is not fully saturated. This is a common challenge in onshore field testing (e.g. McAdam et al. 2020, Tsetas et al. 2023) and may affect the response during pile installation and also subsequent loading where gapping results as discussed in detail in Kementzetzidis et al. (2022, 2023).

In the centrifuge, soil samples can be tested dry or saturated, but replicating cementation as in soils found offshore (or onshore) has proven challenging in the past. Techniques such as microbially induced calcite precipitation (MICP) where native ureolytic soil bacteria facilitate carbonate precipitation, has matured substantially over the past 20 years (e.g. DeJong et al. 2022) and appears promising. Ongoing collaborative research now focuses on sample preparation to reflect the response of complex natural soils offshore, including cemented carbonate sediments, for testing of soil-structure interaction (e.g. piles, drag anchors) in the centrifuge.

Consolidation of fine-grained soils for centrifuge testing may be routine but can prove challenging as well. The seabed in the Baltic Sea has been affected by multiple ice ages, with sites featuring boulders embedded in a hard clay matrix. Clay soils in the laboratory are typically consolidated to much lower undrained shear strengths. Requirements for applied stress to consolidate clay to achieve several MPa undrained shear strength far exceeds the capacity of consolidation presses in use, but also the structural integrity of the sample container and triggers workplace safety concerns.

In order to be able to model monopile installation in the centrifuge that results in pile tip damage from boulder interaction, a minimum cone tip resistance in the clay matrix of 3-4 MPa was targeted in a recent collaborative project. This target undrained shear strength could not be achieved with the existing consolidation press, nor could the press be sufficiently upgraded to produce consolidated clay samples with this target undrained shear strength.

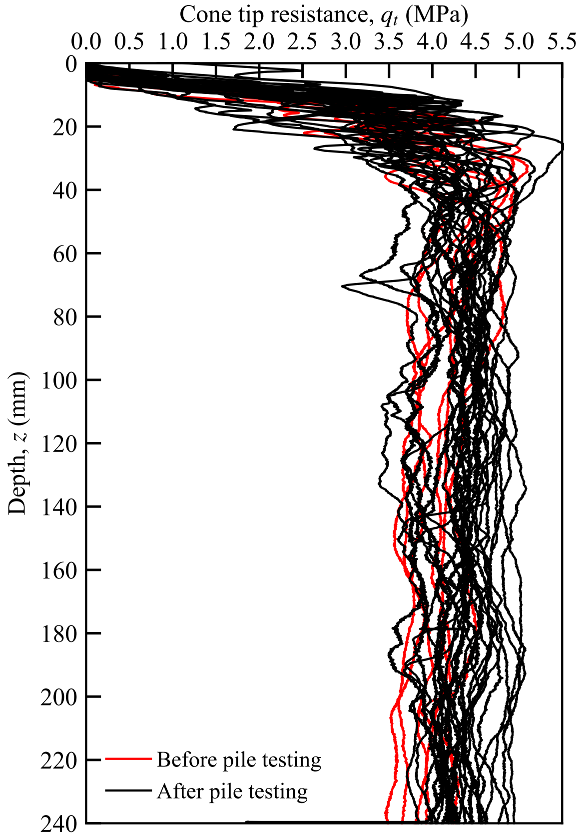

Figure 5. Net cone tip resistance in cemented clay centrifuge sample.

An alternative sample preparation method and protocol had to be developed (Bienen et al. 2023b). This was successful as shown in Figure 5, with net cone tip resistance measured around 4.75 MPa, consistent over the sample depth and the duration of the centrifuge pile testing program. This undrained shear strength was achieved by mixing 18% (by weight) of cement into the kaolin clay slurry, which provided the required strength while allowing consolidation to occur under a maximum consolidation pressure of only 300 kPa.

3 SUCTION BUCKET RESPONSE IN NATURAL SEABED SOILS

3.1 Pressure cyclic suction bucket installation

Suction buckets are installed using a pump which creates a pressure differential inside the bucket compared to ambient conditions and hence applies an additional driving force to the self-weight. In soils with relatively high permeability, e.g. sands, the resulting seepage further reduces the penetration resistance in particular around the skirt tip.

In some conditions, alternatives to monotonic application of the forces may be required to facilitate suction bucket installation to target depth. Pressure cyclic installation, where the downward movement of the suction bucket during installation is periodically reversed through reversal of the pumping action, may be useful in order to limit the applied suction (which may have additional positive implications for plug integrity and structural design requirements).

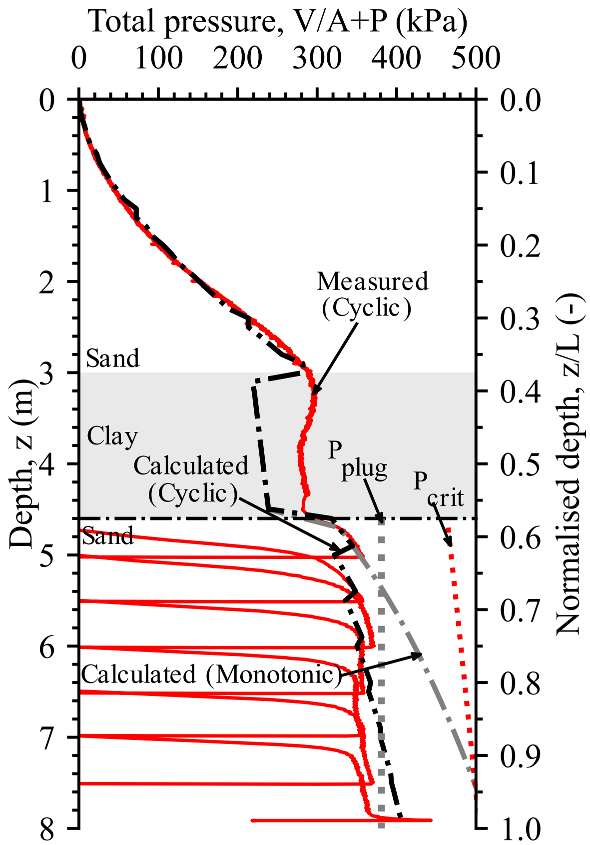

Figure 6. Pressure-cyclic suction bucket installation with prediction based on cyclic CPT results in sand with a sandwiched clay layer (Mani et al, 2024a).

General understanding from testing of model suction buckets using pressure cycling in commercially available soils in the centrifuge has been obtained in recent research, with identification of the potential for pressure cycling to be effective in kaolin clay and silica sand and a prediction method proposed based on cyclic cone penetrometer testing (Mani 2023, Mani et al. 2024a, c).

An example is shown in Figure 6, with the measured suction bucket installation in sand over clay over sand shown in red in terms of applied pressure (vertical load V over suction bucket plan area A plus applied suction P) with depth z in prototype scale (or depth z normalised by the suction bucket skirt length L on the secondary vertical axis). Also shown in Figure 6 is the predicted (calculated) pressure required for this pressure cyclic installation, which was kept below the pressure required to lift the internal plug (P_{plug}) and the critical hydraulic gradient (P_{crit}).

The prediction was tested against field data of suction buckets penetrated into the natural sand over clay seabed by monotonic and pressure cyclic installation, with Figure 7 showing good agreement.

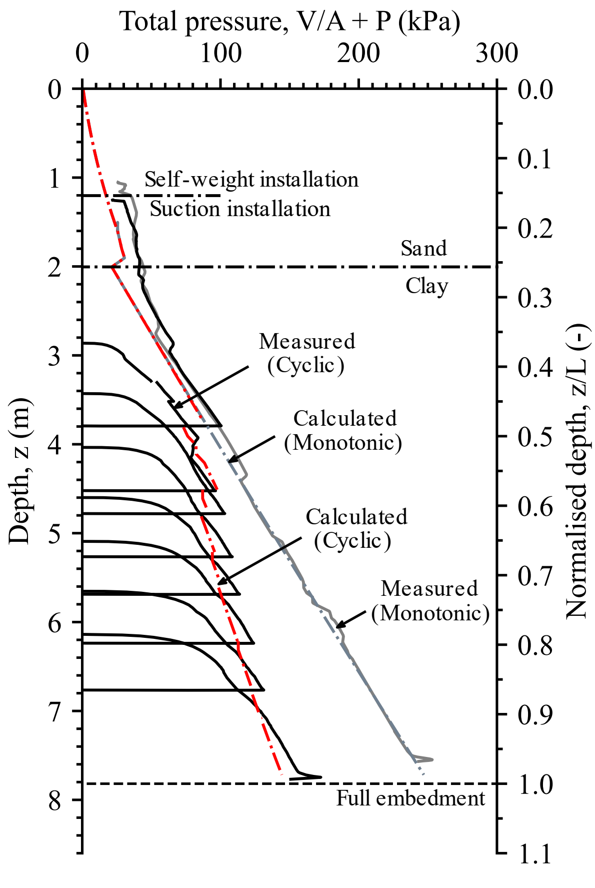

Figure 7. Measured and calculated total pressure during monotonic and pressure cyclic suction bucket installation in sand over clay (field) (Mani et al, 2024c).

Pressure cycling was employed at the Seagreen offshore wind farm, which comprises 114 turbines in deeper water and features significantly more complex soil conditions than sites with previous suction bucket jacket installations for offshore wind in the North Sea. Associated learnings have been shared in e.g. O'Loughlin et al. (2023), Hamdan et al. (2023).

3.2 Centrifuge testing of suction bucket response in soil from an offshore wind farm location

Physical modelling of suction bucket installation and response under subsequent cyclic loading includes medium scale onshore field testing (Kelly et al. 2006), 1g testing at different model scales (e.g. Gütz 2020, Zhu et al. 2011) and small scale testing in a centrifuge (Bienen et al. 2018a, b, Jeong et al. 2019, Pereira et al. 2023). Offshore field testing tends to focus on installation and extraction, i.e. not testing in service performance, with results usually remaining confidential.

Access to sufficient quantities of soil from on offshore wind farm site in Southeast Asia allowed similar testing of suction bucket installation and subsequent vertical cyclic loading relevant to an individual bucket in a suction bucket jacket to be performed in a centrifuge as previously undertaken in commercially available silica sand.

To balance the apparent faster consolidation in the centrifuge due to the drainage path length reduced by N compared to the prototype, testing in sand has typically employed pore fluid with a viscosity N times higher than that of water. Because the natural silty sand from this offshore site behaved like the sandy material in the upper layers albeit with a lower coefficient of consolidation, the material was saturated with water and used to model the natural sandy soil in the centrifuge.

Figure 8a shows the applied stress (vertical load V over plan area A of the suction bucket) and Figure 8b the measured excess pore pressure at the lid invert with the displacement relative to that at the commencement of cycling, Δz, normalised by the suction bucket skirt length L for a pair of tests with average applied stress slightly in compression (B3-S1 with 1 kPa average compressive stress) or tension (B4-S1 with -4 kPa tensile average stress), respectively. There was no accumulation of excess pore pressures and overall similar drainage conditions in both tests (Figure 8b). The cyclic loading was random as in a storm event. Differences in stiffness, as indicated by the coloured dashed lines are about 15% for the largest load cycle (coloured, Figure 8a) but larger for smaller magnitude cycles.

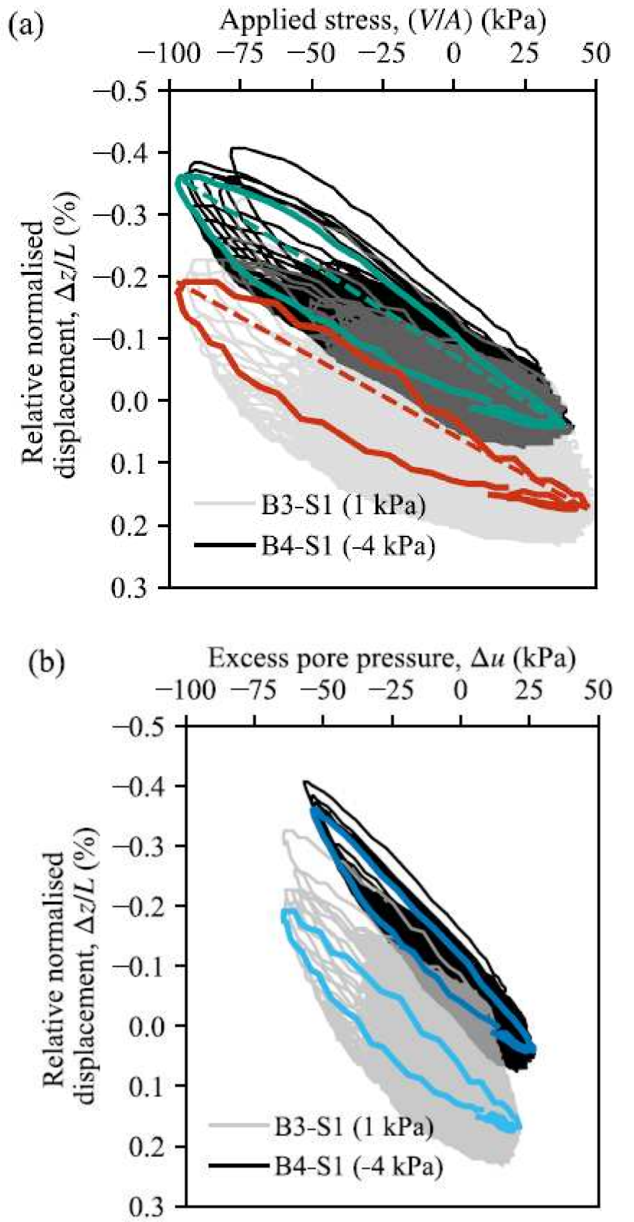

Figure 8. Suction bucket response to vertical cyclic loading in soil from an offshore wind farm site (Mani et al., 2024b), a) applied stress and b) excess pore pressure against relative normalised displacement.

Previous research on commercially available silica sand indicated the resistance against uplift during vertical cyclic loading to significantly exceed that of drained skirt friction, and similar findings were made in this natural silty sand also.

4 CONCLUSIONS

Physical modelling remains an important element in advancing our understanding of soil-structure interaction, obtain evidence, test hypotheses and to form the basis of predictive model development. Significant opportunities exist to improve the link between in situ site investigation and soil-structure interaction predictions for foundation installation (e.g. pressure cycling suction buckets) and in service performance (i.e. under cyclic loading). This may require modification or enhancement of penetrometer testing protocols, and perhaps further development in the suite of penetrometer tools. Direct calibration of soil constitutive model parameters from in situ site investigation data would represent a step change in facilitating complementary numerical modelling.

Physical modelling in the centrifuge of complex soil-structure interaction problems such as vibro-driven pile installation requires new physical modelling apparatus to be developed that cannot simply be miniaturised but has to be re-imagined from scratch.

Commercially available soils enable general research, but physical modelling is increasingly important in soils representative of natural seabed soil conditions as the offshore wind moves into new regions with different seabed soil conditions. Collaboration across specific expertise and disciplines, and integration of geo expertise is needed - just as is done in offshore wind projects in engineering practice - to underpin physical modelling that is relevant.

The example applications included in this paper relate to bottom-fixed offshore wind, but equally apply to anchoring and cabling for floating wind also.

ACKNOWLEDGEMENTS

The author enjoys collaboration and acknowledges input to this paper from colleagues within the Centre for Offshore Foundation Systems (COFS), the National Geotechnical Centrifuge Facility (NGCF) and around the world and is grateful for the financial support provided by the Australian Research Council (ARC), with this paper relating to LP180100024, DP200103466, DP240101808 and LP230100307. The pile field tests are performed by Md Kamrul Ahsan, supervised by Muhammad Shazzad Hossain, Phil Watson and Fraser Bransby. The cemented clay samples and preparation protocols were developed for a collaborative project with Francisco da Silva Pereira and Mark Randolph and project partners Ørsted and Equinor.

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