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Physical model to investigate the effect of multidirectional cyclic loading on monopile foundations

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ABSTRACT: Monopiles for offshore wind turbines (OWT) are subject to multidirectional cyclic loading from wind, waves, and currents throughout their operational lifetime. Despite existing research on the cyclic loading of monopiles, the multidirectional loading effect on the foundation's stiffness and strength properties is still not fully understood. Understanding the behaviour of monopile foundations under such conditions is essential for optimizing OWT designs, enabling more accurate predictions of monopile performance in real-world environmental conditions. A medium-scale 1g model test is underway for a multidirectional loading test on a monopile embedded in loose Hokksund sand. Position sensors, a rotation sensor, and a load cell have been integrated to capture detailed data on strength and stiffness behaviours during loading tests. An industrial electric actuator with a *14.5 kN* capacity has been employed to apply loads to the pile until failure. The loading system has a control unit which can be programmed. A dual orthogonal setup of these programmable actuators will allow the simulation of complex multidirectional cyclic loadings on a pile. Arduino Mega microcontroller is used to program and coordinate all sensors and the actuator. The experimental setup has been substantially completed, with the successful commissioning of both the loading and acquisition systems. The setup aims to generate critical insights into the relationship between loading cycles and stiffness variations, producing strength and stiffness curves. Findings will significantly enhance the understanding of monopile performance and facilitate the advancement of design methodologies for offshore wind energy infrastructure.

Keywords: Offshore Wind; Monopile Foundations; Multidirectional Loading; Strength and Stiffness; Experiment Setup

1 INTRODUCTION

Offshore wind farms can produce more energy compared to onshore wind farms due to stronger and more consistent wind conditions, resulting in a more stable and reliable source of energy (Tumse et al., 2024). Monopiles are commonly used as foundation systems for offshore wind turbines (OWT) because of their simplicity and cost-effectiveness (Shi et al., 2023).

However, studies reflect the thought that the design of these foundations is conservative due to limited knowledge of the behaviour of the foundations specifically for the estimation of displacement accumulation, and fatigue life behaviours (Kallehave et al., 2015).

Monopile foundations for OWT are subjected to multidirectional cyclic loading from wind, waves, and water currents throughout their operational lifetime. Therefore, understanding how monopiles behave under these multidirectional loading conditions is critical for accurately estimating the lifespan of OWT.

A PhD project, part of FRONTIErS-DN program (Prendergast et al., 2024) is currently underway at the Norwegian University of Science and Technology (NTNU) to investigate the influence of multidirectional loading on the stiffness and strength properties of monopile foundations. The displacement accumulation under one-way and multidirectional load cycling will also be tested for a range of load eccentricities.

As part of this research, a 1g experimental model of a monopile is set up in the NTNU geotechnics laboratory, in a 4 m × 4 m × 3 m test tank filled with loose dry sand. The model, constructed at a scale of 1:30, consists of a monopile with a diameter of 27.3 cm and an embedment depth of 108 cm, giving an L/D ratio of 4. The pile will be subjected to lateral loading under both monotonic and cyclic conditions to assess the stiffness change and displacement accumulation properties. Figure 1 shows the sketch of the laboratory setup including the actuator and position sensors, whereas Figure 2 shows the to date physical progress of the setup.

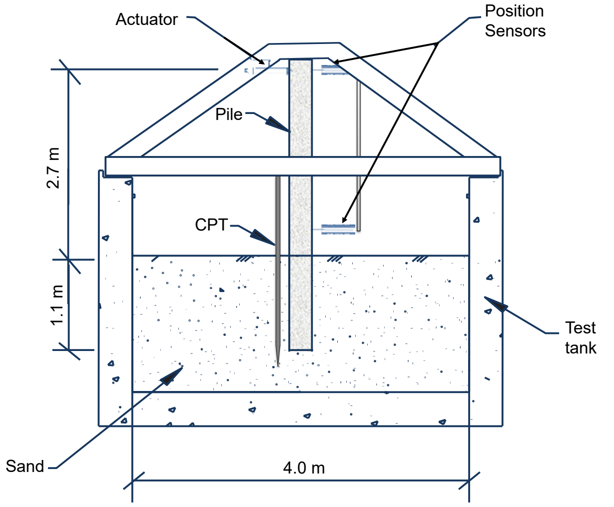

Figure 1. Sketch of the laboratory setup (Not to the scale)

The expected outcomes include detailed strength and stiffness changing behaviour curves for multidirectional loading, prediction of deformation accumulation varying across different load amplitudes, and illustration of the relation between the number of cycles and the corresponding stiffness under multidirectional loading.

This paper presents an overview of the test setup and utilized equipment for the setup at the Norwegian University of Science and Technology for a multidirectional cyclic loading test of monopiles embedded in sand.

2 PHYSICAL MODEL SETUP

This section outlines the materials and procedures used in the test setup, including pile driving method, and pre- and post-pile installation CPTs. Each procedure is designed to create a standardized environment to ensure repeatability and testing consistency.

2.1 Sand

The sand in the laboratory is Hokksund sand, sourced from a glacifluvial deposit in south-eastern Norway (Moen, 1978). The sand has been treated to suit for laboratory purposes where fine and coarser particles were removed. Most particle diameters range from 0.3 to 0.8 mm, with no particles below 0.1 mm or above 1.0 mm. The physical properties of the sand used in the test tank, with a relative density of 72 %, are described in Table 1.

The relative density, unit weight, and the corresponding friction angle of the sand can be determined from Table 2, based on the nozzle opening size, which is discussed in the next section.

Figure 2. Test Setup for CPT after pile driving

2.2 Sand Tank and Pluviation Method

A concrete sand tank at NTNU is equipped with sand raining system as illustrated by Lieng (1988) in Figure 3. The spreader passes back and forth over the tank with raining sand until manually stopped by an operator when the required depth of sand is reached. One pass of a spreader over the test tank can rain approximately 10 cm layer of sand.

Table 1. Hokksund sand physical properties (Moen, 1978)

Parameter	Unit	Value
Friction angle, $\boldsymbol{\varphi}$	*degrees*	38.0
Min. void ratio, $\boldsymbol{e_{min}}$	-	0.56
Max. void ratio, $\boldsymbol{e_{max}}$	-	0.95
Relative density, (D_R)	%	72
Average unit weight, $\boldsymbol{\gamma}$	kN/m^3	16.0
Specific unit weight, $\boldsymbol{\gamma_s}$	kN/m^3	27.1
Mean grain size, $\boldsymbol{D_{50}}$	mm	0.42

This air pluviation method offers several advantages, including the ability to reconstitute a uniform and homogeneous sand medium, as well as ensuring reproducibility (Mortazavi Bak et al., 2024). Lieng

(1988) investigated the unit weight variation with depth, and the effect of the air pluviation method on sand density reproducibility, finding that despite the gradually decreasing falling distance of sand particles, the density change remained insignificant.

The spreader nozzles can be changed to achieve different sand densities. Moen (1978) studied the relationship between the size of nozzle openings, sand density, and friction angle, and is presented in Table 2. The nozzle opening size used in this setup is 16 mm, which will give a relative density of 72 %.

Table 2. Average density and friction angle with size of nozzle opening (Moen, 1978)

Nozzle opening size, mm	Density, kN/m^3	Void ratio, %	Relative Density, %	Friction angle, degrees
5	*17.1*	0.56	100	39.1
10	16.6	0.60	88	38.9
16 *	16.0	0.66	72	38.0
20	15.1	0.76	48	36.9

* Used nozzle opening size in this setup

The test tank has nine gates at the bottom that can be opened to remove sand and transfer it to the silos through the conveyor belts below. The dimension of the test tank which is 4 m × 4 m × 3 m makes it possible to avoid boundary effects (Achmus et al., 2007) for medium-scale tests.

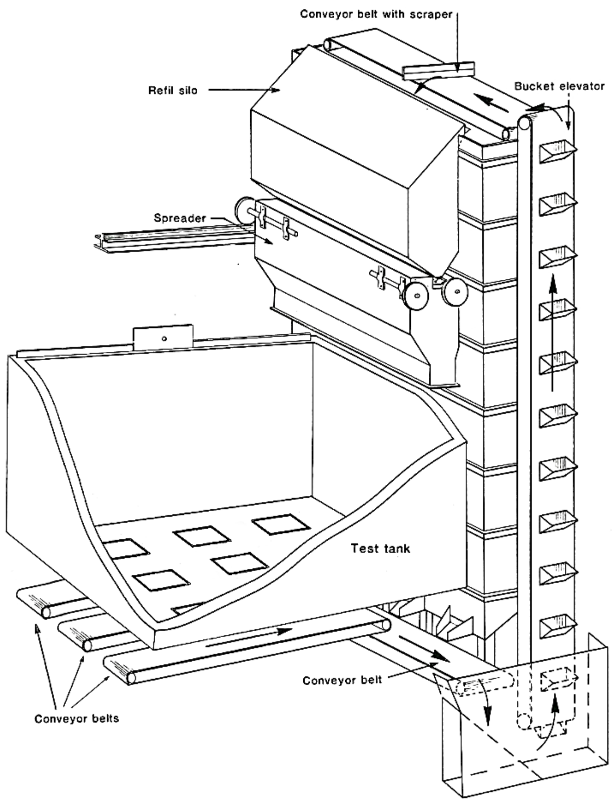

Figure 3. Sand tank with sand raining system, sketch by Lieng (1988)

2.3 Monopile Model

The model uses a 1:30 scale to represent a monopile foundation of approximately 8 m in diameter and 32 m in length which gives an aspect ratio (L/D) of 4.0. The pile is made from a steel pipe of 27.3 cm in outer diameter. The rigidity of the pile is ensured by optimizing the thickness of the pile and the embedded pile length in accordance with Poulos and Hull (1989).

$$K_R = \frac{E_p I_p}{L^4 E_{SL}} \begin{Bmatrix} < 0.0026 \; flexible\;piles \\ > 0.208 \quad rigid\;piles \end{Bmatrix} \qquad (1)$$

For loose sand with Young's modulus, $E_{SL} = 20\,MPa$ (Obrzud, 2010), an embedded pile length, $L = 108\,cm$, and a wall thickness of, $t = 4\,mm$ satisfied the rigidity of the pile with $K_R = 0.236 > 0.208$.

The pile loading point, referred to as eccentricity, is positioned 2.7 m above sand level.

2.4 Pile Driving

The pile was lifted to a certain height with a crane, and verticality was checked using a spirit level. The crane was then lowered until the pile reached the sand level. The crane was released to allow the pile to sink freely into the sand while the pile was supported laterally to avoid rotation. Approximately 7 cm of embedment was observed due to the pile's self-weight.

A hammering technique was employed to drive the pile deeper to the required depth, utilizing a hammer weight of 30 kg. The weight is raised to an approximate height of 30 cm for each drop onto the pile head delivering a forceful impact that effectively penetrates the loose sand. Verticality checks were performed at intervals to minimize initial deflection before testing. Once the pile reached the required depth, verticality was re-evaluated, showing a deflection of 0.25 degrees in one direction and 0.75 degrees in the orthogonal direction.

Settlement due to densification was observed in the sand surrounding the pile, with the highest settlement of 2.5 cm occurring immediately adjacent to the pile as illustrated in Figure 4. A cone penetration test (CPT) was conducted to further investigate the effect of the dynamic pile driving technique on the initial state of the sand.

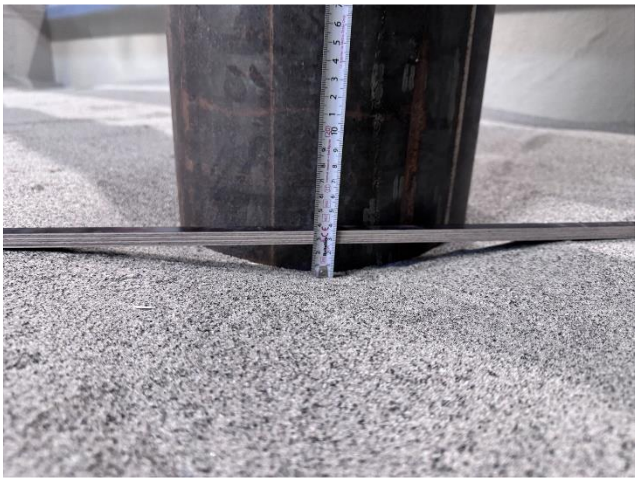

Figure 4. Settlement due to densification around the pile

2.5 Cone Penetration Test (CPT)

A digital CPT Cone and Geotechnical Sensor Network (GSN) from Geomil Equipment has been used for a CPTest. The CPT setup is shown in Figure 2. Data acquisition software from the same company is used. CPT was conducted both before and after pile installation to assess the impact of installation on the densification of the surrounding sand. The tests were performed at a standard penetration rate of 2.0 cm/s for an approximate depth of 1.2 m to ensure measurements through the pile length. As shown in Figure 5, the result indicates a significant increase in the tip resistance of the sand following pile installation. The CPT was performed 5 cm from the edge of the pile as shown in Figure 1 and Figure 2 to capture the immediate densification effects. However, additional CPTs at varying distances from the pile are required to better characterize the extent of soil densification around the pile.

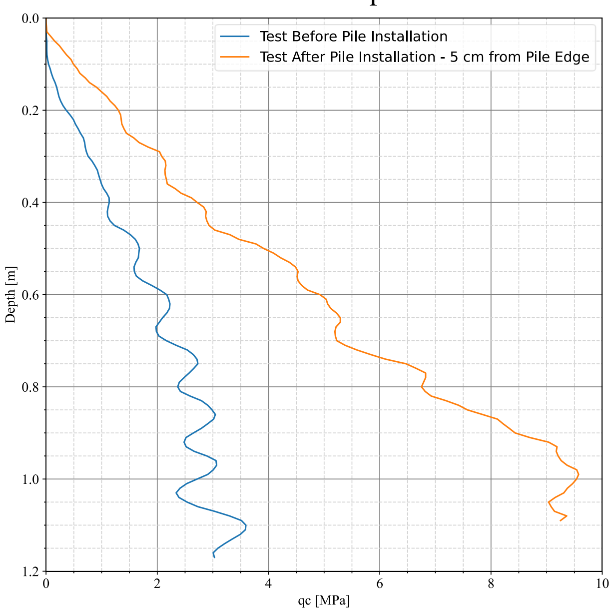

Figure 5. CPT results, q_c, before and after pile installation

The fluctuation in tip resistance observed in the CPT result can be attributed to the layering structure of the sand as described in section 2.2.

3 INSTRUMENTATION

The instrumentation setup, including the loading system and data acquisition system for the tests are described in this section. The loading system, was selected based on a prediction from a numerical analysis result. Whereas, a data acquisition system was carefully selected to fit the precise and frequent data collection throughout.

3.1 Loading System

A preliminary Finite Element Analysis of the model under a monotonic lateral loading has been performed using PLAXIS 3D to simulate the behavior of loose sand with properties similar to those intended for laboratory use. The analysis result, shown in Figure 7, indicates that, at a failure point, the pile has a lateral capacity of 13 kN when a load is applied at 2.73 m above sand level. Failure is defined as a deflection of 25% of the pile diameter at sand level, which corresponds to 6.25 cm in the prototype.

Based on the analysis results, an industrial electric actuator with a 14.5 kN capacity and 30 cm stroke length has been purchased from FESTO, Germany – which is high enough to exceed the pile's expected 13 kN lateral capacity. Figure 6 shows components of the loading system, which primarily consists of an electrical actuator, servo motor, and controller.

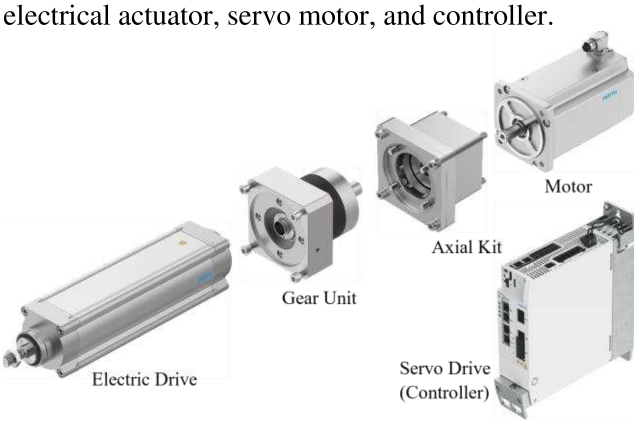

Figure 6. Main components of the loading system

The servo motor operates on 400 V three-phase power, achieving a maximum rotational speed of 5,150 rpm. Together, this system can deliver a full-cycle lateral load within 1.75 seconds.

The monopile model will be equipped with this loading system arranged in an orthogonal direction where each loading unit can be programmed independently.

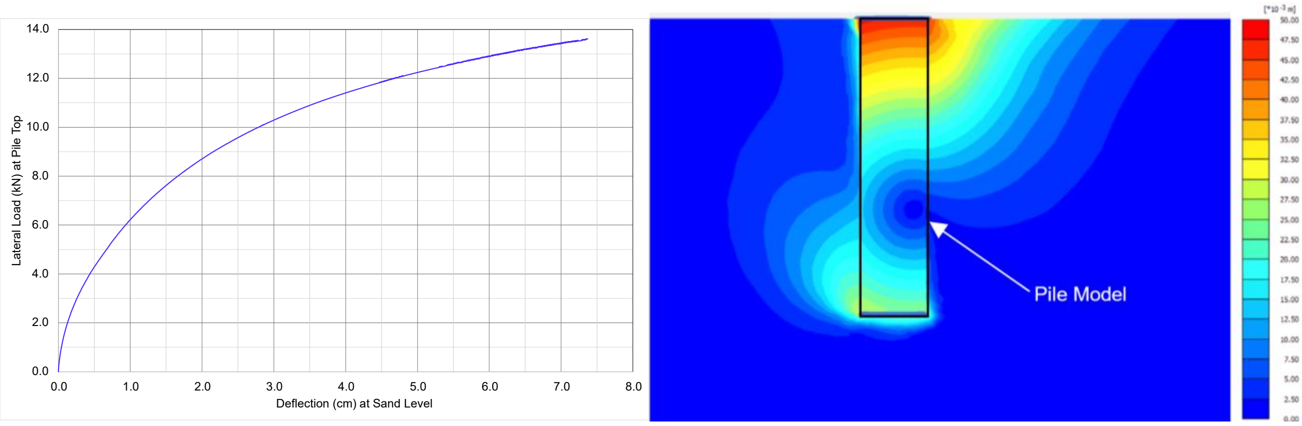

Figure 7. FE analysis to predict the response of physical model test; Load-deflection curve at pile top[left] and total displacement of sand particles [right]

The key advantage of this setup is that the controller of the orthogonal loading units can be linked to a computer and programmed to deliver the desired cycle frequency, displacement, and variable speed settings.

In addition, connecting two of these loading systems to the pile in orthogonal directions and programming them accordingly allows for the delivery of a resultant force that can change direction and magnitude, enabling the simulation of complex multidirectional loading patterns beyond regular cyclic loading.

The designed configuration allows the actuators to freely adjust their force direction in the horizontal plane without rigid constraints. This is achieved by mounting each actuator to the support structure using two perpendicular revolute joints. As a result, the actuators can rotate around their vertical axis and tilt in response to pile deflection. In addition, a rod eye joint is used to securely connect the actuators to the pile cap, ensuring a flexible load transfer mechanism.

3.2 Data Acquisition System

Position sensors will be strategically placed on the monopile model to capture its response under monotonic, unidirectional, and multidirectional cyclic loading conditions. A specific type of position sensor, Cable extension sensors from ASM, Germany, are used to determine the linear displacements. This position sensor has a resolution of 0.002% of its full-scale range, providing accuracy down to 0.01 mm over a measurement range of 500 mm.

In addition to the position sensors, an inclinometer with model number 8.IS40.22321 from Kubler, made in Germany, is utilized to determine the rigid rotation movement of the monopile during loading. This inclination sensor can measure 2-axis inclinations in the measuring range of ±45°. Its high shock resistance capacity combined with high resolution and accuracy, makes this device suitable for the project.

A load cell with a capacity of up to 20 kN is integrated into the setup to measure applied loads during testing. The load cell is capable of measuring both tension and compression, allowing for monitoring of loads under two-way cyclic loadings.

The position sensors, load cell, and inclinometer are to be connected to an Arduino Mega microcontroller, which is programmed to log readings. Data readings from all sensors will be taken before and after each load increment and at intermediate intervals. Further analysis of the collected data will define the load-time-deflection curves.

4 CONCLUSIONS

The design of the experimental test setup has been completed, and the loading system has been successfully tested under a monotonic load. The setup integrates various equipment with a programming unit to ensure coordination and monitoring during testing. Currently, the research is in its early phase to undertake tests and obtain results. The test setup aims to generate valuable data on strength and stiffness characteristics, contributing to the development of more effective design methodologies for monopile foundations. Additionally, results from tests under multidirectional cyclic loading will provide insights for numerical analysis, improving modelling accuracy by understanding how stiffness in one direction is influenced by cyclic loading from multiple directions.

AUTHOR CONTRIBUTION STATEMENT

First Author: Data curation, FE Analysis, Test Setup, Writing- Original draft.
Second Author: Writing- Reviewing and Editing, Supervision.

Last Author: Test Setup, Methodology, Writing-Reviewing and Editing, Supervision, Funding acquisition.

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