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Integrating physical testing and numerical modelling to investigate behavior of monopiles in sand under lateral cyclic loading

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ABSTRACT: Accurate prediction of response under cyclic lateral loading remains challenging for monopile foundations supporting offshore wind turbines (OWTs). This study proposes an integrated physical-numerical framework to improve the understanding and prediction of pile response under drained monotonic and cyclic lateral loading in sand. Model tests were performed on a well-controlled instrumented pile (diameter $0.27\ m$, length $4\ m$; $1.1\ m$ embedded) in dense dry sand, recording load-displacement behavior in order to derive secant stiffness evolution, hysteresis, and ratcheting displacements. These data form the basis for validating finite element analyses with advanced constitutive models. To reproduce the monotonic response, the Hardening Soil Small Strain model is applied in PLAXIS 3D ™ and used to calibrate stiffness and strength parameters of the SANISAND-MS model. The Sanisand-MS model is employed to capture cyclic behaviors. The combined methodology provides insights into the constitutive behavior of soil, helping to bridge the gap between observed responses in the physical model and the overall behavior and performance of the monopile. The analysis reveals that the depth of the point of rotation of monopile is not a static parameter but changes through cyclic loading. In addition, a significant dilation of the sand in the vicinity of the monopile near the soil surface was recorded, changing from an initial state of $e = 0.71$ at the first cycle to $e = 0.79$ by the 100th cycle.

1 GENERAL

Offshore Wind Turbines (OWTs) have emerged as a promising source of energy, driven by global demands for green and sustainable power generation. Several OWT farms are already in operation, with rapid future growth projected. Among different types of foundations for OWTs, monopiles remain the leading solution due to their cost-effectiveness and ease of installation. Monopile foundations are subjected to complex environmental loads, including millions of load cycles from wind and waves. While the design must ensure the ultimate lateral capacity of these piles (Ultimate Limit State), the design is frequently governed by strict Serviceability Limit State (SLS) criteria (DNV, 2014). These standards impose rigorous limits on permanent deformation and accumulated rotation to ensure the operational efficiency of the turbine (Bhattacharya & Adhikari, 2011). Consequently, the investigation of monopile response regarding permanent deformation/rotation has become a primary area of interest in recent geotechnical research, e.g. Abadie et al. (2023) and Leblanc et al. (2010).

While global deformation is the visible result, the underlying mechanisms are governed by complex soil-structure interaction and internal soil state changes. This paper aims to enhance the understanding of monopile response by integrating physical model testing with advanced numerical analysis. While physical modelling provides explicit observation of global performance, such as permanent deformation and rotation accumulation over load-cycles, it is limited to study constitutive soil behaviors. Calibrated numerical models are employed to investigate behaviors that cannot be directly captured experimentally, e.g. the migration of the center of rotation. Thereby providing a constitutive basis for the observed physical responses. The combining method highlights the importance of integration of experimental observations into the modelling process to improve the understanding of pile response and design predictions.

The paper focused on numerically analyzing the monopile's response to lateral monotonic and cyclic loading under drained conditions in sand. Two constitutive models were employed to capture the different aspects of the foundation's behavior. The Hardening Soil (HS) model was used to simulate the monotonic loading response, as it effectively captures stress dependent stiffness and primary loading behavior in soils. The SANISAND-MS model was utilized for simulating certain aspects of cyclic behavior, focusing on the constitutive behavior of soil elements under short term cyclic loading. Change in depth of pile rotation point, variation of void ratio through load cycles and behavior of stress path is investigated in this study.

The model parameters were calibrated for Hokksund sand using laboratory triaxial test data conducted at the Norwegian Geotechnical Institute (Kildalen, 1982; Kildalen, 1976), supported by insights from 1g lateral monotonic and cyclic pile load tests (Zerihun et al., 2025).

2 LABORATORY MODEL SETUP

A physical testing program was conducted at NTNU in a 4 m × 4 m × 3 m sand tank as a 1g experiment. The monopile model was constructed from a steel pipe with an outer diameter of 0.273 m. It was embedded in dense dry Hokksund sand, which was prepared by air pluviation. The physical properties of sand and pile used are presented in Table 1 and Table 2 respectively. The monopile installation method was dynamic pile driving. The pile's embedment length was 1.08 m, resulting in a length to diameter ratio (L/D) of 4 (Zerihun et al., 2025). Afterwards, the monopile was subjected to lateral monotonic and cyclic loading. The load-displacement results from these physical tests were used to validate the numerical models developed in this study.

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

Parameter	**Unit**	**Value**
Min. void ratio, $\boldsymbol{e_{min}}$	-	0.56
Max. void ratio, $\boldsymbol{e_{max}}$	-	0.95
Void ratio, $\boldsymbol{e_0}$	-	0.66
Friction angle, $\boldsymbol{\varphi}$	*degrees*	38.0
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
Coefficient of uniformity	-	2.04

Table 2. Model Pile physical properties

Parameter	**Unit**	**Value**
Diameter, $\boldsymbol{D}$	m	0.273
Thickness, $\boldsymbol{t}$	m	0.004
Total height	m	4.0
Embedded depth, $\boldsymbol{L}$	m	1.08
Pipe bending stiffness, $\boldsymbol{EI}$	kNm^2	6116
Steel unit weight	kN/m^3	78.50

3 NUMERICAL MODEL

Numerical simulations were performed using the finite element software PLAXIS 3D ™ to replicate the physical experiments. Exact dimensions of the laboratory setup discussed previously were adopted for the numerical model for both the soil domain and the monopile. All vertical boundary planes were normally fixed, constrained to allow only movement tangent to the plane, while the bottom boundary was fully fixed. The top surface of the sand was left unfixed.

A full 3D model as shown in *Figure 1* was developed to allow for subsequent extension of the analysis to multidirectional loading scenarios. However, given the initial symmetrical nature of the model geometry and loading, a half-symmetry model with appropriate boundary conditions could have been alternatively employed to significantly reduce the computational time.

The numerical domain was discretized using 10-noded tetrahedral elements. A total of approximately 7000 elements were used for the full 3D model. To enhance accuracy in capturing the localized soil-structure interaction, a reduced mesh coarseness factor was applied for soil elements around the pile perimeter, where the largest plastic deformation and strain rates were expected to occur.

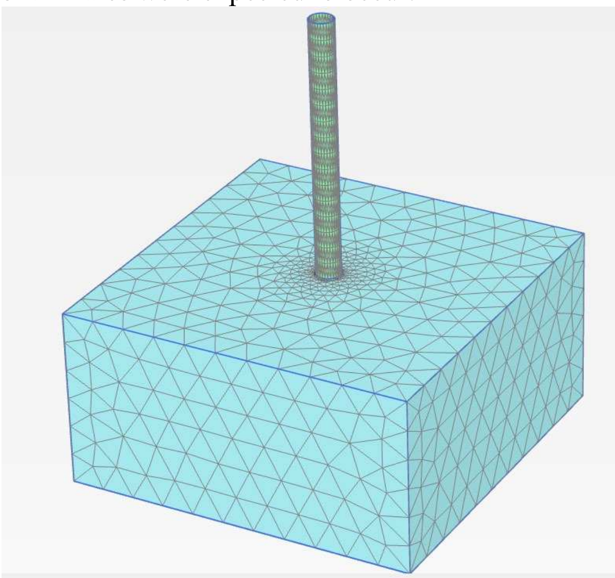

Figure 1: PLAXIS 3D Model

Table 3. SANISAND-MS Material Set used for Hokksund Sand

Parameter	Description	Value	Parameter	Description	Value
G_0	Shear modulus coefficient	230	C_h	Hardening parameter	1.01
υ	Poisson's ratio	0.10	A_0	Dilatancy parameter	0.820
c	Ratio b/n critical stress ratios in triaxial ext. and compr.	0.712	n^b	e dependent bounding yield surface parameter	2.80
M_c	Stress ratio at critical state in compression	1.20	n^d	e dependent dilatancy surface parameter	1.17
λ_c	Slope of the CSL in the compressibility plane	0.049	μ_0	Ratcheting parameter	750
ξ	Critical state line exponent	0.270	ζ	MS Shrinkage parameter	0.0001
m	Size of the yield surface	0.010	β	Dilatancy memory parameter	1
h_0	Hardening parameter	4.0	e_{ini}	Initial void ratio	0.66
e_0	Void ratio of the CSL at p=0 kPa	0.845	$M^{b,max}$	Maximum bounding stress ratio in triaxial compression	2.09

4 SOIL/MATERIAL SETS

Two constitutive models were used throughout the modelling. A hardening soil small strain model for monotonic loading has been used with the material parameters shown in *Table 4*. The parameters taken from a test on similar work after Hanssen (2016).

Table 4. Hardening Soil Material Set for Hokksund Sand

Parameter	Unit	Value
$E_{s,50}^{ref}$	[MPa]	82.04
E_{oed}^{ref}	[MPa]	70.0
E_{ur}^{ref}	[MPa]	190
υ_{ur}	[-]	0.2
m	[-]	0.5
c'_{ref}	[kPa]	0.1
φ	[°]	38.0
ψ	[°]	5
γ	[kN/m^3]	16.0

A material set of SANISAND-MS (Liu et al., 2020) has been used for the cyclic loading analysis. The model parameters were calibrated specifically for the Hokksund sand. The calibration relied on primary laboratory data, including triaxial tests performed at NGI (Kildalen, 1982) and direct observations from a 1g physical testing program involving lateral monotonic and cyclic pile load tests. In addition, few parameters for SANISAND-MS, such as Poisson's ratio, and maximum bounding stress ratio, $M^{b,max}$, were taken as recommended by plaxis manual. The material set parameters are given in Table 3.

SANISAND-MS gives insight into the first few cycles of the loading. Since the model is an implicit method of computation, it takes more computational time to run lots of cycles and is not practical for long term cyclic deformation analysis. In this regard, the HCA model is recommended to analyze the accumulated displacement of pile under several thousands of load cycles. This model is specifically designed to simulate the accumulation of plastic strain over a large number of cycles, $N > 1000$, (Niemunis et al., 2005).

5 SIMULATION AND VALIDATION

A series of finite element simulations was performed to calibrate the numerical model against the 1 g laboratory test results and for the primary analyses. Two distinct monotonic loading simulations were conducted to evaluate the performance of the adopted constitutive models. The first simulation used the HS-small model. The lateral load was applied at the top of the pile, replicating the exact loading conditions of the physical laboratory model. The HS model was also used to calibrate the elasticity parameters of SANISAND-MS model.

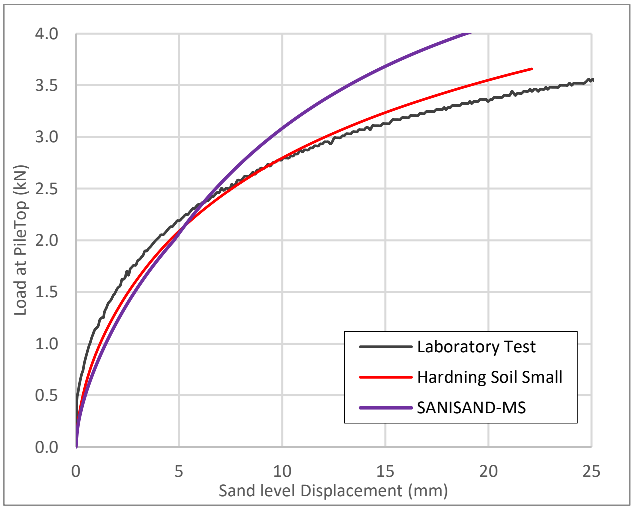

Figure 2: Comparison of Plaxis Results for Monotonic Loading

A second monotonic analysis was performed using the SANISAND-MS model. This simulation established pre-cyclic loading. The load-displacement results from the PLAXIS analysis were compared against the laboratory test results, as illustrated in Figure 2. While the SANISAND-MS simulation exhibited a response that was initially too soft followed by an overly strong ultimate response, the overall model was considered satisfactory for the purpose of this study.

To capture the complex cyclic behavior of the monopile, the SANISAND-MS was employed to simulate the response during the first hundred load cycles. Figure 3 compares the cyclic analysis result with laboratory test. The SANISAND-MS model significantly overestimates the rate of displacement accumulation. However, it qualitatively captures the essential features of the soil-pile interaction and used here to evaluate the qualitative response of the monopile. A more rigorous calibration of the model parameters using more laboratory dataset is required to enhance the accuracy of numerical analysis.

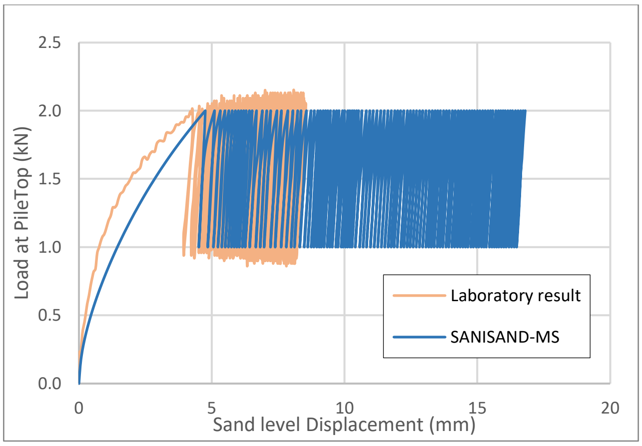

Figure 3: Comparison of PLAXIS analysis with laboratory results

100 load cycles have been simulated in plastic analysis. A python script is added to duplicate 200 loading and unloading phases in plaxis.

6 RESULTS

6.1 Change in Rotation Point of Monopile

The results of the numerical analysis, using the SANISAND-MS constitutive model, reveal a change in the rotation point (the depth at which the lateral displacement is zero) under cyclic lateral loading. The results demonstrate that cyclic loading influences the monopile's rotation point. However, the magnitude of this shift was not significant over the analyzed 100 load cycles. This slight shifting is indicative of a redistribution of soil resistance and a change in the soil-structure interaction.

In addition, the rate of shifting decreases following a hyperbolic function. The following figure shows the change in depth of rotation point with respect to number of cycles.

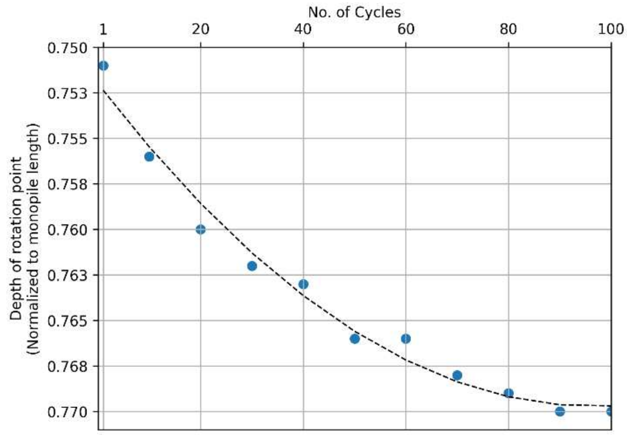

Figure 4: Variation of the depth of rotation point

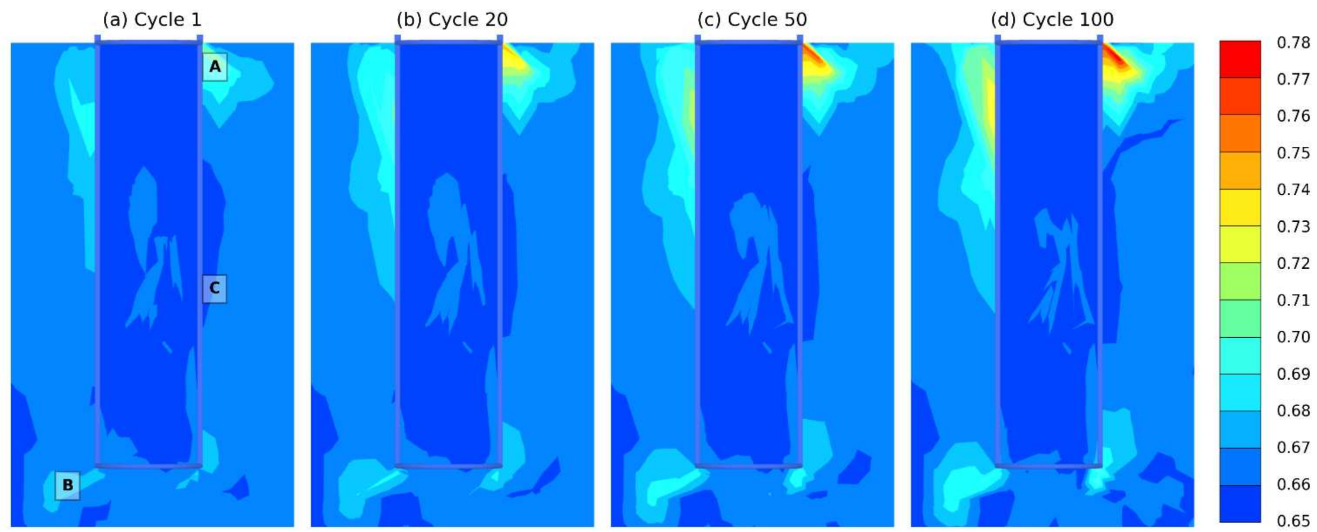

Figure 5: Visual variation of void ratio in different zones of soil elements at different load cycles

6.2 Change in void ratio, Δe

The change in void ratio was monitored at three locations (point A, B, and C, as illustrated in Figure 5a).

Point A (Primary Passive Zone), located in front of the pile face, experienced the most substantial cyclic loosening. The void ratio increased from an initial e=0.71, at the beginning of cyclic loading, to 0.79. This significant dilation is primarily due to the proximity of the free surface.

Point B (Rear-Bottom Zone), located at the back-bottom of the pile, exhibited a moderate increase in void ratio. This localized response is attributed to soil dilatancy and a gradual stress increase at this location.

Point C (Pile waist), in contrast, showed negligible changes in void ratio. Being located close to the center of rotation, this zone experiences limited cyclic effects, and the lateral confinement remains relatively low.

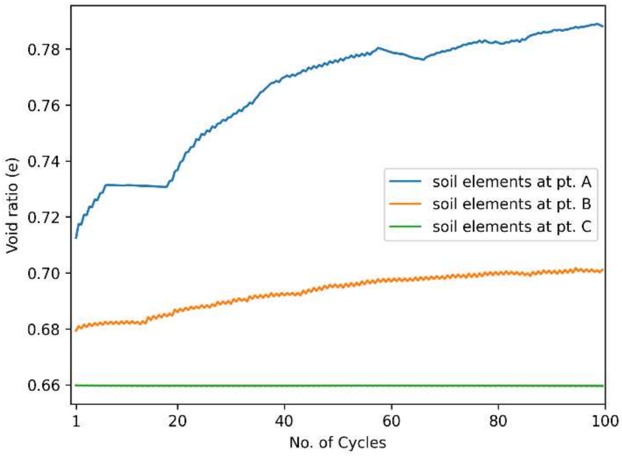

Figure 6: Change in void ratio for three locations in Figure 5a

7 CONCLUSIONS

This study investigated the response of monopiles under cyclic lateral loading using PLAXIS 3D. The numerical analyses provide insights into the constitutive and state-dependent evolution of the soil pile system over 100 load cycles. The rotation point of the monopile is observed to shift slightly downward during cyclic loading. The rate of change in depth of the rotation point is mostly significant during the initial cycles, following a decreasing hyperbolic behavior. A substantial increase in void ratio was observed, specially on soil elements in front of the pile close to soil surface. However, further investigation is required to generalize these observed responses, specifically, extending the analysis to include different load levels, initial void ratios, and pile geometries is important to further develop the conclusions.

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