Proceedings of the 5th ECPMG 2024
5th European Conference on Physical Modelling in Geotechnics
2-4 October 2024, Delft, the Netherlands
© 2024 the Authors

Monopile under lateral loading: centrifuge testing and numerical investigation

O. Orakci
KU Leuven, Bruges, Belgium, olgu.orakci@kuleuven.be
The University of Melbourne, Melbourne, Australia

L. Simonin
UC Louvain, Louvain-la-Neuve, Belgium, luc.simonin@uclouvain.be

T. Quinten, M.A. Cabrera
TU Delft, The Nederlands, t.o.quinten@tudelft.nl, m.a.cabrera@tudelft.nl

S. François
KU Leuven, Leuven, Belgium, stijn.francois@kuleuven.be

G. Anoyatis
KU Leuven, Bruges, Belgium, george.anoyatis@kuleuven.be

S. Chow, Y. Tian
The University of Melbourne, Melbourne, Australia, shiaohuey.chow@unimelb.edu.au, yinghui.tian@unimelb.edu.au

H. Rattez
UC Louvain, Louvain-la-Neuve, Belgium, hadrien.rattez@uclouvain.be

ABSTRACT: Monopiles are widely used as a supporting structure for offshore wind turbines. Their response directly affects the overall behavior and performance of the offshore wind turbine system; thus, they have been a focal point of extensive research in the last decade. The need for three-dimensional FEA modeling of the foundation and the importance of selecting an appropriate soil constitutive model have been demonstrated by recent studies (e.g., the PISA project), setting a cornerstone in the offshore wind industry. In this underway study, the lateral loading response of offshore wind turbine monopiles in dense to very dense sand is investigated through an extensive testing program using the geo-centrifuge at TU Delft. The experimental results obtained at 50-g will be upscaled to the prototype scale for comprehensive analysis. Key aspects of this study include the comparison of the lateral response under monotonic loading via numerical analyses performed with PLAXIS software. The numerical simulations span a broad spectrum, from basic models to sophisticated methods based on critical state theory, enhancing the accuracy of predictions to realistically capture the findings from experimental pushover analysis. By bridging experimental and numerical approaches in a high-fidelity testing environment, this study strives to contribute essential knowledge and valuable insights for enhancing the reliability and performance of monopile foundations in challenging offshore conditions.

1 INTRODUCTION

The growing global demand for energy is driving efforts to expand offshore wind energy production to new heights. The REPowerEU Action Plan, as outlined in the Esbjerg Offshore Wind Declaration, aims to achieve 150 gigawatts of offshore wind energy by 2050 (Wind Europe, 2022). Achieving such objectives underscores the importance of thoroughly designing offshore wind turbines (OWTs) with a precise and reliable process to avoid operational interruptions or breakdowns, and guarantee energy provision at the expected rate. Foundation design is an essential part of this design process. Most OWTs are founded on monopiles, large open-ended steel tubes driven into the seabed. In recent years, the design process of monopiles has evolved, with the integration of the PISA method by the designer (Byrne et al., 2017), which heavily relies on finite element examination of the foundation system. This examination requires the use of an appropriate soil constitutive model. Soil constitutive models provide relations for the entire incremental stress-strain response of soils to describe their mechanical properties under different loading conditions, such as the cyclic loads imposed by wind and waves.

While conducting extensive tests on these massive structures is costly and impractical, centrifuge tests offer a viable alternative by replicating failure mechanisms, stresses, and strains. Centrifuge testing is useful for OWT monopiles as it can aid in comprehending the behavior of monopiles in both dry and saturated sandy soils under diverse conditions.

This paper aims to simulate the pushover of a monopile in the 50-g geo-centrifuge at TU Delft by numerical analyses through a range of soil models varying from fundamental models: 1) Mohr-Coulomb (MC) and 2) Hardening Soil (HS) to more advanced models: 3) Hypoplasticity model with intergranular strains (ISHP) and 4) NorSand. The numerical simulations of the 1/50 scale model and the prototype (for comparison reasons) are conducted in PLAXIS 3D (Bentley, 2020). The objective of the paper is to gain insight from a comparison of the lateral response under monotonic loading between experimental data and numerical analyses. However, the experimental campaign is underway, such that this paper mainly focuses on the numerical study, while the oral presentation at ECPMG24 will tackle the comparison between the experimental results and the numerical simulations that are presented herein.

The paper is structured as follows: Section 2 explains the test program using the geo-centrifuge at TU Delft. Section 3 introduces the soil models with their calibration parameters. Section 4 presents the results of the finite element analysis (FEA). Section 5 concludes the main findings.

2 EXPERIMENTAL SET-UP

The lateral loading response of offshore wind turbine monopiles in dense to very dense sand is planned to be investigated through an extensive testing program. The centrifuge tests at 50-g will be carried out at TU Delft.

The prototype pile has a diameter of 1.25 meters and a wall thickness of 25 mm. The embedment length-to-diameter ratio (L/D) is 5. The loading eccentricity within the centrifuge is 2.4D above the mudline. Although the testing program includes both saturated and dry samples, for this preliminary study only dry conditions were simulated. The saturated conditions will be studied, both experimentally and numerically in the future. Similarly, soil relative density of 60% is selected for the simulations even though a wider range of relative densities are tackled in the centrifuge tests.

This pile is vibratory-driven (Simonin et al., 2024) in a 295 mm diameter and 195 mm high container filled with GEBA sand. GEBA sand (SIBELCO, 2014), a type of industrial high silica sand, is used in the tests at TU Delft. Its fine and uniform grain size facilitates physical soil modeling, assuming consistent initial conditions.

The lateral loading actuator of TU Delft is designed to operate at a maximum centrifuge acceleration of 100g; it has a maximum lateral capacity of 5 kN. The rendered image of the TU Delft lateral loading actuator is given in Figure 1. The rig is designed to integrate with existing pile installation hardware at TU Delft to subject pile foundations to lateral loading directly after installation, without the need to intermittently stop the centrifuge. As such, the stress state around the pile is preserved, leading to a better approximation of field conditions. The lateral loading frame is fixed to a stainless-steel baseplate, secured by four clamping rings onto the vertical columns of the TU Delft centrifuge carrier. This configuration makes the vertical position of the loading frame fully adjustable, allowing for adjustments to the loading position with respect to the soil surface, adding to the flexibility of the actuator.

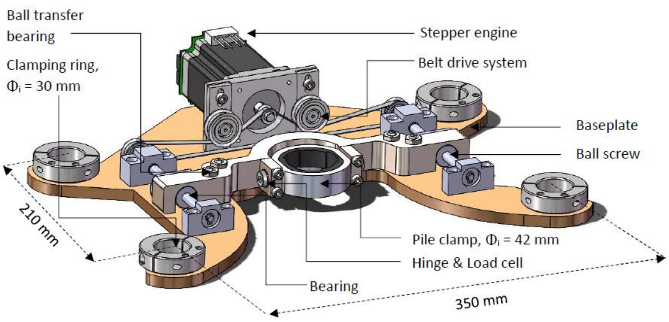


Figure 1. Rendered image of the TU Delft lateral loading actuator.

The loading frame is driven by a Trinamic PD60-4-1160 stepper engine. A belt system connects the engine to two ball screws, which convert the rotational movement of the main axle into lateral movement. Each ball screw incorporates a bearing connecting to one end of the loading beam. To counteract the perpendicular gravitational force on the baseplate, the loading beam features four adjustable ball transfer bearings that minimize moments on the ball screws. The pile clamp is in the middle of the loading arm. This part consists of a stainless-steel outer ring and a removable 3D-printed insert. The latter makes it possible to accommodate piles with a diameter of up to 50 mm, $D_{0,max}$. Rotational hinges on either side of the pile clamp facilitate unhindered rotation during lateral loading. The arms housing the rotational bearings are fitted with a temperature-compensated load cell consisting of four XY-strain gauges in full Wheatstone bridge configuration. The movement of the pile is tracked using a laser triangulation sensor mounted on the strongbox, thereby decoupling it from actuator-induced deformations.

An in-house control unit operates the loading frame either in load or displacement control mode. For the maximum pile diameter of 50 mm, the operational loading frequency for bi-directional cyclic loading is 1Hz. The corresponding displacement range is $0.01D_{0,max}$ in either direction. The actuator can accommodate displacements up to $0.1D_{0,max}$ at the mudline for monotonic loading.

3 SOIL MODELS AND PARAMETER CALIBRATION

A wide range of soil models are experimented within this study, starting with the classical 1) Mohr-Coulomb (MC) model (Coulomb, 1776; Mohr, 1900), which shows 'linear-elastic-perfectly-plastic' material behavior, to more advanced models. These models include 2) Hardening Soil (HS) (Schanz et al., 1999), which can capture the stress dependence of stiffness and strength together with the strain dependence of stiffness. Critical state dependent 3) Hypoplasticity model with intergranular strains (ISHP) (Niemunis, 2003) and 4) NorSand model (Jefferies, 1993) are also employed in the study. The latter critical state (CS) models are developed for granular soils to cover and represent a wide range of confining stresses and densities. While the intergranular strain concept allows the model to predict small strain stiffness degradation and cyclic loading effects, NorSand can capture work-hardening plasticity.

Soil parameters for GEBA sand are well documented in the literature. This study employs the available soil model calibration properties across different studies. Following Chavez (2017), the unit weight of soil is considered to be 18 kN/m^3, and the maximum, minimum, and critical void ratios are 1.28, 0.64, and 1.07, respectively. Soil relative density is considered 0.6 in the simulations, and the related void ratio, e, is 0.812. The soil model parameters for MC and HS are adopted from Chavez (2017) and given in Table 1 and Table 2, respectively. ISHP soil model parameters are employed from the study of Spyridis and Lopez-Querol (2023) and are provided in Table 3. NorSand soil model parameters for GEBA sand are adapted from Bierma (2022) and listed in Table 4.

Table 1. MC model parameters for GEBA sand (p_{ref}=3 kPa)

Parameter	Symbol	Value	Unit
elastic modulus	E	700	kPa
Poisson's ratio	ν	0.2	-
cohesion	c	0	kPa
friction angle	ϕ	46.5	°
dilatancy angle	ψ	12	°

Table 2. HS model parameters for GEBA sand (p_{ref}=1 kPa)

Parameter	Symbol	Value	Unit
reference elastic modulus	E_{50}	700	kPa
oedometer stiffness	E_{oed}	700	kPa
unloading stiffness	E_{ur}	2800	kPa
cohesion	c	0	kPa
peak friction angle	ϕ	47.2	°
dilatancy angle	ψ	12	°
Poisson's ratio	ν	0.2	-
power exponent	m	0.6	-
failure ratio factor	R_f	0.8	-
lateral pressure at rest	K_0	0.426	-

Table 3. ISHP soil model parameters for GEBA sand (p_{ref}=1 kPa)

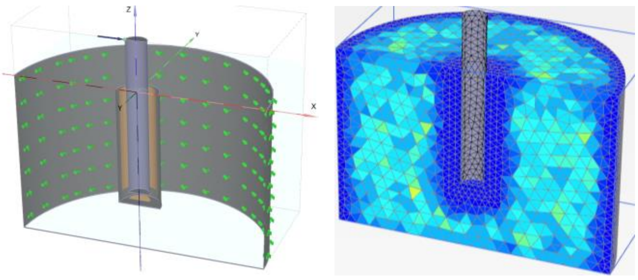
Parameter	Symbol	Value	Unit
friction angle	ϕ_{cv}	34	°
shift of p due to cohesion	p_t	0	MPa
hardness	h_s	2.5e3	MPa
exponent	n	0.3	-
factor alpha	a	0.11	-
factor beta	b	2	-
factor of 180° dir. change	m_R	5.5	-
factor of 90° dir. change	m_T	3.9	-
max intergranular strain	R	1e-4	-
degradation factor	β_R	0.3	-
degradation factor	χ	0.7	-

Table 4. NorSand soil model parameters for GEBA sand

Parameter	Symbol	Value	Unit
reference shear modulus	G_{ref}	385	-
reference mean pressure	P_{ref}	100	kPa
elasticity exponent	n_G	0.5	-
Poisson's ratio	ν	0.2	-
CSL parameter	C_a	0.953	-
CSL parameter	C_b	0.06	-
CSL parameter	C_c	0.32	-
CS friction angle	ϕ_{cv}	31.8	°
CS friction ratio	M_{tc}	1.278	-
stress ratio parameter	N	0.42	-
dilatancy parameter	χ_{tc}	4.06	-
hardening parameter	H_0	150	-
hardening parameter	H_ψ	0.0	-
OCR	R	1.0	-
softening flag	S	1.0	-
initial state parameter	ψ_o	-0.174	-

4 NUMERICAL SIMULATIONS

The centrifuge model undergoes a gradual increase in centrifugal acceleration from 1-g to 50-g during the spin-up process. Simultaneously, the soil specimen experiences a corresponding increase in centrifugal acceleration, impacting its stress state. A 1/50 scaled model working on this principle and the upscaled prototype are simulated for comparison purposes. The centrifuge tests were modeled using PLAXIS 3D (Bentley, 2020), commercial FEA software incorporating various soil constitutive models. The mesh size is considered based on the sand container described previously. The pile is represented as an elastic steel plate, while the soil elements are depicted as 10-node tetrahedral elements. Due to the symmetry of the model and the loading, half of the foundation system is modeled to enhance computational efficiency. Around the pile, the mesh is refined in a cylindrical area with two times the pile diameter. The model is fully fixed at the bottom and fixed in x and y directions at the surrounding cylinder to represent the sand container in the simulation. The boundary conditions and the meshed model are shown in Figure 2(a) and Figure 2(b), respectively.

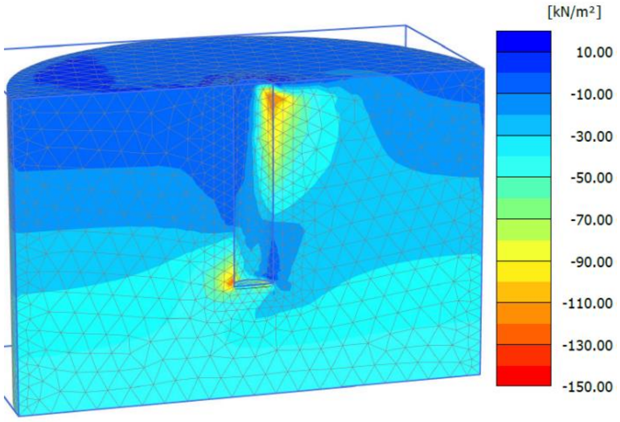


(a) (b)

Figure 2. The FEA model (a) boundary conditions and loading, (b) mesh.

In the analyses, the monopile is considered wished in place (WIP), while the installation effects, with the comparison of hammering and vibratory driving, will be the subject of future studies. Strength reduction with R=0.4 was applied at the interface between the pile and the soil to address the soil structure interaction following Abdel-Rahman and Achmus (2005). At the bottom of the pile, an interaction between soil – soil without any strength reduction is defined to allow for a relative displacement of the soil inside the pile and the underlying soil layer. In the scaled model, an additional phase is incorporated following the WIP stage to simulate the 50-g acceleration experienced in the centrifuge. This approach allows gravity control through the total load multiplier for material weights, denoted as ΣM_{weight}, by setting its value to 50.

Comparing the simulation of the geo-centrifuge scale model and the prototype scale model for the MC model, the stresses and displacements observed in the scaled model align perfectly with those in the prototype, thereby validating the success of the centrifuge modeling process. The cartesian effective stress σ'_{xx} contours are shown in Figure 3.



(b)

Figure 3. Cartesian effective stress σ'_{xx} under 200 kN scaled load for the full model.

Predictions are made using soil constitutive model parameters calibrated by various researchers, as detailed in Section 3. These predictions are then compared in a preliminary study, while they will be compared to the actual centrifuge test results underway during the 5th ECPMG. Mudline displacement comparison for pushover analyses with different soil constitutive models are presented in Figure 4. This process is undertaken to gain valuable insights on the test. It can be seen in the figure that, except for the MC model, all the predictions are quite close under the given load. Since the MC model is not density-dependent, and the elasticity modulus increment is not assigned to the soil layer, the confining pressure effect on the modulus of elasticity is not reflected in the results. This causes a weaker soil behavior in the simulation since the parameter is calibrated under low confining pressure.

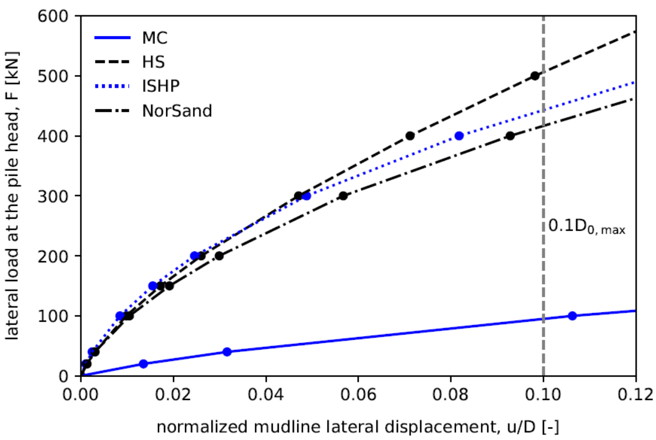


Figure 4. Normalized mudline displacement comparison for pushover analyses with different soil constitutive models.

5 CONCLUSIONS

This paper compares pushover analyses using the geo-centrifuge at TU Delft and numerical simulations using soil constitutive models with a broad spectrum, from basic models to sophisticated methods based on critical state theory. The main findings of this work can be summarized as follows:

- Numerically, the 1/50 scale model and the upscaled prototype have the same lateral response under monotonic loading as expected.
- Since model parameters are calibrated towards certain tests via different sets of parameters, the results are also calibration-dependent, as anticipated. However, simulation results show quite close estimates of lateral load-displacement under the given loads.

The experimental data will be compared with the predictions once the test results become available. It will be the main focus of the presentation at ECPMG24.

ACKNOWLEDGEMENTS

This research was supported by the Cyclic soil-structure interaction framework for the foundations of offshore renewable energy structures project, funded by the “KU Leuven Global PhD Partnerships with The University of Melbourne” scheme (GPUM/21/023) and “The University of Melbourne Chancellery Strategic International Research Collaboration funds”. The underway experimental campaign at the geotechnical centrifuge of TU Delft is funded by the GEOLAB project, European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 101006512.

REFERENCES

Abdel-Rahman, K., & Achmus, M. (2005). Finite element modelling of horizontally loaded monopile foundations for offshore wind energy converters in Germany. In Proceedings of the international symposium on frontiers in offshore geotechnics. Taylor and Francis, Perth (pp. 391-396).

Bentley (2020). PLAXIS 3D-Reference Manual CONNECT Edition V20.03

Boulanger, R. W., & Ziotopoulou, K. (2015). PM4Sand (Version 3): A sand plasticity model for earthquake engineering applications. *Center for Geotechnical Modeling Report No. UCD/CGM-15/01, Department of Civil and Environmental Engineering, University of California, Davis, Calif.*

Bierma, S. (2022). Modelling a Cone Penetration Test in Dry Sand using the Material Point Method: A State-Dependent Constitutive Model Approach.

Byrne, B. W., McAdam, R. A., Burd, H. J., Houlsby, G. T., Martin, C. M., Beuckelaers, W. J. A. P., Zdravković, L., Taborda, D. M. G., Potts, D. M., Jardine, R. J., Ushev, E., Liu, T., Abadias, D., Gavin, K., Igoe, D., Doherty, P., Skov Gretlund, J., Pache, S., and Plummer, M. A. L. (2017). “PISA: New design method for offshore wind turbine monopiles”. *Proceedings of the 8th International Conference on Offshore Site Investigation and Geotechnics (SUT OSIG).* London, UK, pp. 142–161.

Chavez Abril, M. A. (2017). Numerical simulations of static liquefaction in submerged slopes.

Coulomb, C. A. (1776). Essai sur une application des regles des maximis et minimis a quelques problemes de statique relatifs a l'architecture: Memoires de l'Academie Royale pres Divers Savants. Paris, 7, 343.

Jefferies, M. G. (1993). Nor-Sand: a simple critical state model for sand. *Géotechnique, 43*(1), 91-103.

Liu, H. Y., Abell, J. A., Diambra, A., & Pisanò, F. (2019). Modelling the cyclic ratcheting of sands through memory-enhanced bounding surface plasticity. *Géotechnique, 69*(9), 783-800.

Mohr, O. (1900). Welche Umstände bedingen die Elastizitätsgrenze und den Bruch eines Materials. *Zeitschrift des Vereins Deutscher Ingenieure, 46*(1524-1530), 1572-1577.

Niemunis, A. (2003). *Extended hypoplastic models for soils* (Vol. 34). Vienna: Inst. für Grundbau und Bodenmechanik.

SIBELCO (2014). GEBA. Technical Data Sheet. SIBELCO.

Schanz, T., Vermeer, P. A., & Bonnier, P. G. (1999). The hardening soil model: formulation and verification. *Beyond 2000 in computational geotechnics, 1*, 281-296.

Simonin, L.E.J, Rattez, H., Herman, B., Wehbe, T., Orakci, O., Anoyatis, G., Francois, S. (2024) “Investigation of vibro-driven monopiles in a geo-centrifuge”. *Proceedings of the 5th European Conference on Physical Modelling in Geotechnics*, 2-4 October 2024, Delft, the Netherlands. Submitted.

Spyridis, M., & Lopez-Querol, S. (2023). Numerical investigation of displacement pile installation in silica sand. *Computers and Geotechnics, 161*, 105591.

Wind Europe (2022). North Sea offshore wind to help repower the EU. Retrieved from https://windeurope.org/newsroom/press-releases/north-sea-offshore-wind-to-help-repower-the-eu/. Accessed on 2023-02-28.

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 5th European Conference on Physical Modelling in Geotechnics and was edited by Miguel Angel Cabrera. The conference was held from October 2nd to October 4th 2024 at Delft, the Netherlands.

To see the prologue of the proceedings visit the link below:

https://issmge.org/files/ECPMG2024-Prologue.pdf