Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Liquefaction-induced response of offshore wind turbine monopiles: from centrifuge tests to numerical modelling

Masoumeh Asgarpoor[*], Eva Brunschweiler[**], Ioannis Anastasopoulos[**], Mahdi Taiebat[*]
[*]*University of British Columbia, Vancouver, BC, Canada, asgarpur@mail.ubc.ca, mtaiebat@civil.ubc.ca*
[**]*ETH Zurich, Switzerland, eva.brunschweiler@igt.baug.ethz.ch, ioannis.anastasopoulos@igt.baug.ethz.ch*

ABSTRACT: This study investigates the seismic response of offshore wind turbine (OWT) monopiles in liquefiable soils by integrating centrifuge test data with advanced numerical simulations. Element tests conducted at ETH Zurich and centrifuge tests at the University of Cambridge are used to calibrate and validate a fully coupled dynamic finite element (FE) model in OpenSees employing the SANISAND-MSf constitutive model. The constitutive model is calibrated for Hostun sand using monotonic triaxial and cyclic direct simple shear tests and is used to simulate the seismic response of a monopile foundation in a stratified loose-over-dense sand profile. Dynamic analyses capture key liquefaction mechanisms, including excess pore pressure generation and monopile rotation, and selected results demonstrate that the numerically predicted monopile rotation is broadly consistent with experimental observations at the system level, with implications for the seismic assessment and design of offshore wind turbine monopile foundations.

1 INTRODUCTION

Offshore wind turbines (OWTs) installed in regions of high seismicity and underlain by saturated sandy soils are susceptible to liquefaction-induced effects. These may lead to a significant reduction in shear resistance and stiffness of the sand surrounding the monopile, thereby diminishing the foundation capacity to support operational loads applied to the OWT superstructure and potentially causing excessive rotation of the tower. Several studies have investigated the seismic response of OWT monopiles in liquefiable soils (e.g., Kementzetzidis et al., 2019; Liu & Kaynia, 2023). However, further research is required to evaluate the effectiveness of soil constitutive models and numerical approaches in accurately capturing such complex system-level response.

2 CAMBRIDGE CENTRIFUGE TESTS

This study investigates the response of an OWT monopile subjected to combined seismically induced liquefaction and monotonic environmental loading, based on centrifuge model tests conducted at the University of Cambridge (Español-Espinel et al., 2024). The prototype-scale model consisted of a 17.5 m long, 7.11 m diameter monopile embedded in Hostun sand, with the upper 7 m in loose ($D_r \approx 40\%$) and the lower 10.5 m in dense sand ($D_r \approx 90\%$). The 48 m long tower was an aluminium tube with a lumped mass at the top representing the Rotor–Nacelle Assembly (RNA), connected to the monopile through a moment-resisting transition piece. After spin-up, during which the centrifugal acceleration increased to 70 g, lateral environmental loading was applied at the RNA using a hanging mass, followed by base excitation with a frequency of 1 Hz, 10 cycles, and a peak ground acceleration (PGA) of 0.2 g. The tower settlement and rotation were measured using LVDTs installed on both sides of the tower.

3 NUMERICAL SIMULATION

A fully coupled nonlinear dynamic analysis of a 3D OWT monopile founded in liquefiable soil is conducted, employing the FE computational platform OpenSees (McKenna et al., 2000). The monopile is modelled with eight-node SSPbrick elements, while the soil is represented using SSPbrickUP elements with a coupled displacement-pore pressure formulation. Soil behaviour under pre- and post-liquefaction conditions is captured using the SANISAND-MSf model (Yang et al., 2022), calibrated for Hostun sand based on monotonic triaxial (Tam, 2024; Borgesi, 2024) and cyclic direct simple shear tests (Kassas et al., 2021). A thin continuum layer of degraded Hostun sand is used to model the soil-pile interface. The OWT tower is modelled using elastic beam-column elements with a length of 1 m, with lumped masses assigned at the nodes and a larger lumped mass at the top to represent the RNA. The 3D FE model is shown in Figure 1. Lateral boundaries are tied in the x direction. Owing to symmetry in the y

direction, only half of the geometry is modelled, and nodes along the axis of symmetry are constrained in the y direction. Pore water pressure is fixed at surface nodes and free below the surface to enable the generation of excess pore water pressure. Following geostatic initialization under gravity loading, the static lateral load is applied at the RNA level, followed by seismic excitation.

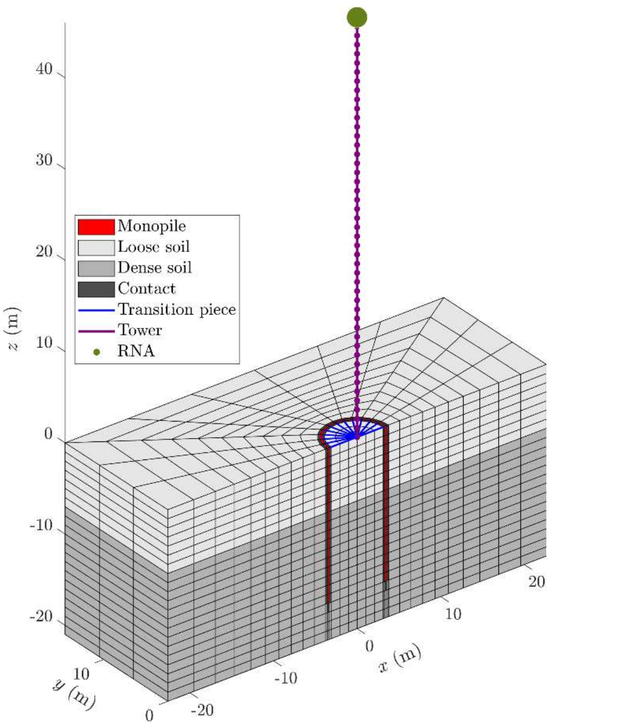

Figure 1. Finite element model of the OWT founded on a monopile in saturated Hostun sand.

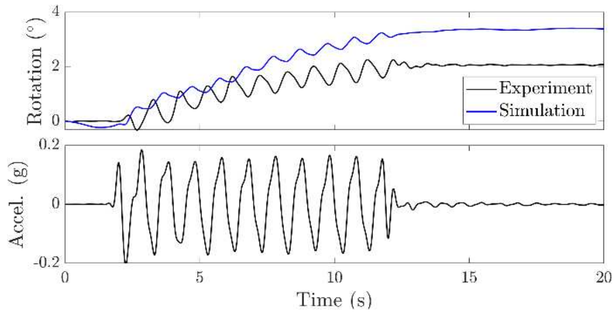

Figure 2. OWT rotation during dynamic loading.

4 RESULTS

The 3D FE modelling results show the evolution of OWT rotation during dynamic loading, under the combined effects of static wind loading and seismic excitation. As shown in Figure 2, the analysis indicates the development of a permanent tower rotation of approximately 3.4° in the clockwise direction, consistent with the direction of the static moment generated at the tower base by the applied lateral load at the RNA level. The permanent rotation predicted by the simulation is larger than that measured in the experiment; however, both exceed the Serviceability Limit State (SLS) threshold of 0.5° within the first few loading cycles following the onset of earthquake excitation.

5 CONCLUSIONS

This study explored the capability of the numerical model to simulate the liquefaction-induced response of an OWT monopile in saturated sand subjected to combined static and dynamic lateral loading. The tower rotation is accumulated during dynamic loading in the direction of the moment induced by the applied static lateral load and can exceed the SLS threshold after a few loading cycles. More broadly, this study illustrates how advanced constitutive and numerical modelling, when integrated with centrifuge testing, can support system-level interpretation and generalization of liquefaction-induced monopile response.

6 REFERENCES

Borgesi, A. (2024). *Characterization of Hostun Sand and Calibration of the SANISAND-MS Model*. Master thesis, ETH, Zurich, Switzerland.

Español-Espinel, C., Haigh, S.K., Madabhushi, G.S., Abadie, C.N., Go, J.E., Morrison, P.R. (2024). Evolution of excess pore water pressures around monopiles subjected to moderate seismic loading. *Soil Dyn. and Earthq. Eng.*, 176, 108316.

Kassas, K., Adamidis, O., Gerolymos, N., Anastasopoulos, I. (2021). Numerical modelling of a structure with shallow strip foundation during earthquake-induced liquefaction. *Géotechnique*, 71(12), 1099-1113.

Kementzetzidis, E., Corciulo, S., Versteijlen, W.G., Pisano, F. (2019). Geotechnical aspects of offshore wind turbine dynamics from 3D non-linear soil-structure simulations. *Soil Dyn. and Earthq. Eng.*, 120, 181-199.

Liu, H., Kaynia, A.M. (2023). Characteristics of cyclic undrained model SANISAND-MSu and their effects on response of monopiles for offshore wind structures. *Géotechnique*, 73(4), 294-309.

McKenna, F., Fenves, G.L., Scott, M.H., Jeremic, B. (2000). Open system for earthquake engineering simulation. *PEER*, Univ. of California, Berkeley, CA, USA.

Tam, A. (2024). *Characterization of Hostun Sand and Calibration of the IC MAGE M14 Model*. Master thesis, ETH, Zurich, Switzerland.

Yang, M., Taiebat, M., Dafalias, Y.F. (2022). SANISAND-MSf: a sand plasticity model with memory surface and semifluidised state. *Géotechnique*, 72(3), 227-246.