Multi-Mode Scaling of Offshore Wind Turbine Models for DONISIS Seismic Centrifuge Tests

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ABSTRACT: Geotechnical centrifuges enable reproduction of prototype stress conditions in reduced-scale models by subjecting them to an enhanced gravitational field. In the context of offshore wind research, they are widely used to investigate seismic soil-structure interaction (SSI), often with the superstructure replaced by a simplified scaled model, tuned to match only the first bending mode of the prototype. While straightforward to design and fabricate, such models neglect higher bending modes, which can significantly influence the seismic response of offshore wind turbines (OWTs). This study presents a scaling methodology for fabricating centrifuge-scale OWT models that preserve the key dynamic properties of the prototype. The resulting model more accurately reproduces prototype behaviour than a conventional first-mode–tuned model, as demonstrated by numerical validation with linear seismic analyses. The optimised design was 3D-printed and tested in the ETH Zurich Geotechnical Centrifuge Centre (GCC). Experimental results confirmed close agreement with target modal properties, validating the proposed methodology.

1 INTRODUCTION

Centrifuge model testing reproduces realistic soil stress conditions at small scale and enables reliable, cost-effective investigation of complex problems. This capability is particularly important for seismic soil–structure interaction, where both soil material nonlinearity and coupled soil–structure dynamics must be accurately scaled. As offshore wind development expands into seismically active regions, simplified centrifuge approaches used for wind and wave loading on monopile foundations become insufficient. Earthquakes excite multiple vibration modes and require full dynamic similitude of both soil and structure (Sah & Yang, 2024; Panagoulias et al., 2023). This study reports very recent research on the design of dynamically consistent centrifuge models for offshore wind turbines, illustrated through a downscaled support structure of a 14 MW Siemens Gamesa turbine within the DONISIS project (Pisanò et al., 2024).

2 DOWNSCALING METHODOLOGY & EARLY EXPERIMENTAL FINDINGS

The OWT considered in this study is based on a reference design representative of next-generation offshore wind farms in seismically active regions such as the Asia–Pacific. The monopile-supported support structure has a mudline diameter of 9.0 m and an embedment depth of 29.0 m, founded in very dense sand (relative density 90%). The first three eigenfrequencies of the prototype were identified numerically as $f_{1,2,3}$ = 0.15, 0.82, 1.55 Hz.

A novel downscaling methodology is employed to preserve dynamic similitude of the support structure. Finite Element Model Updating (FEMU) is performed using an optimisation algorithm implemented in OpenSees, ensuring close agreement with the prototype in terms of eigenfrequencies, mode shapes, and effective modal mass. SSI is modelled in a simplified manner using a Winkler approach with locally calibrated linear elastic springs following He & Kaynia (2024), with a constant damping ratio of 2% of critical assigned to all modes.

The performance of the dynamically consistent model is numerically studied under the notorious Kobe JMA earthquake and compared with the full-scale prototype. Mudline bending moment comparison (Fig. 1) shows very close agreement and indicates that the seismic response is dominated by the second bending mode.

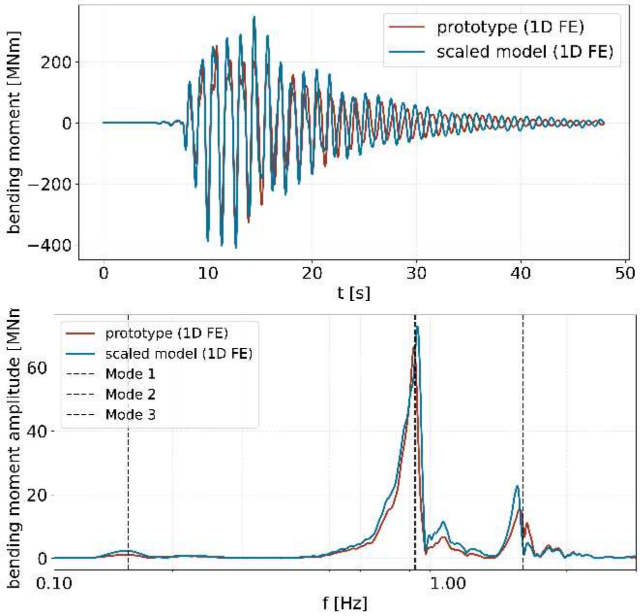

Figure 1. Comparison of mudline bending moment between prototype and model (prototype scale)

○ Fig. 2 presents the Frequency Response Function (FRF) between accelerometers at the top mass and on the pile (at 17.0 m depth), showing close agreement with the targeted eigenfrequencies. Note that the first eigenfrequency cannot be reliably identified from the FRF due to the negligible contribution of the first mode.

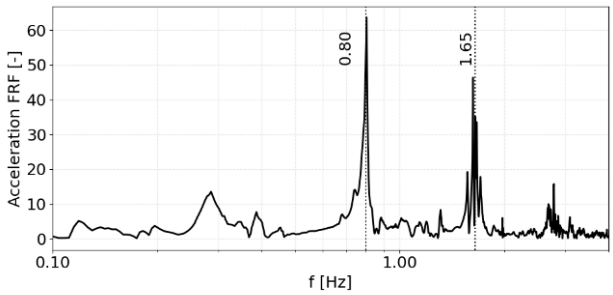

Figure 2. Accelerations FRF from centrifuge test results (prototype scale)

3 CONCLUSIONS

The proposed downscaling methodology successfully preserves the key dynamic characteristics of the offshore wind turbine, including higher-mode behaviour that governs seismic response. Physical centrifuge model tests confirm close agreement between the targeted and measured eigenfrequencies, validating the FEMU-based design approach. Models relying solely on first-mode scaling are shown to be inadequate for seismic loading, underscoring the need for full dynamic similitude in offshore wind turbine centrifuge modelling.

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