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Study on Wet-Towing Transportation of Offshore Wind Turbines with Suction Piles

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Extended Abstract

With the global demand for sustainable energy surging, offshore wind turbines (OWTs) have become increasingly vital. However, the transportation and installation of these massive structures remain a significant challenge, especially under environmental, logistical, and safety constraints. To address this, the present study proposes a wet-towing strategy for suction pile-based OWTs that exploits the natural buoyancy of suction piles and eliminates the need for heavy offshore lifting. The paper introduces a novel finite element method (FEM) tailored to analyze the floating mechanics of bottom-opened suction piles under air pressure and hydrodynamic forces, thereby providing a systematic approach to model and verify the wet-towing process. The study first details the development of a finite element formulation that incorporates nonlinear air pressure stiffness, based on Boyle-Mariotte law, and hydrostatic forces arising during flotation. A beam-element-based FEM is used to represent suction piles as floating cylinders with open bottoms, accounting for variations in air volume and internal pressure due to submergence depth. The theoretical derivation is validated through a Newton-Raphson solution scheme, and the resulting stiffness matrices are used to compute vertical and rotational responses under applied loading. To ensure the fidelity of the method, the FEM model was verified against both theoretical and experimental benchmarks. Static analyses of a vertically floating bottom-opened cylinder showed excellent agreement between analytical solutions and finite element results, confirming the method's robustness in capturing air compression effects and floating stiffness. Subsequently, a floating platform with three suction piles was simulated, with validation against theoretical rigid-body motion equations for translation and rotation. The proposed model successfully reproduced displacement and moment responses under external loads, reinforcing its applicability to multi-pile systems.

A comprehensive case study was then conducted involving the wet-towing of a 15 MW OWT jacket support structure. The support system consists of a triple-suction pile foundation, designed and modified from an IEA reference turbine model to optimize buoyancy and towing stability. Finite element analysis, incorporating large-displacement dynamics and hydrodynamic loads, was executed under 18 different wind and wave load scenarios based on DNV design load cases. The time-history simulations employed Newmark integration to capture structural behavior under irregular wave and wind-induced forces. Key metrics such as stress ratios, tugboat power requirements, and structural inclination angles were monitored throughout. The results demonstrate that wet-towing is feasible under moderate sea conditions (wave height $\leq$ 1.09 m and average wind speed $\leq$ 7 m/s). Under such conditions, structural stress ratios remained within safe limits, and required tugboat power did not exceed rated capacities. However, stress ratios increased with wave heights, particularly in column and brace members, indicating vulnerability to dynamic loading and potential resonance of the cantilevered suction piles. Moreover, wave and wind directions significantly influenced both the transmitted forces and structural rotation, with transverse directions exacerbating stress yet reducing tugboat load. The study highlights several benefits of the wet-towing approach, including reduced greenhouse gas emissions, minimized offshore assembly work, and lower operational costs. By eliminating the need for offshore grouting and heavy-lift vessels, the proposed method streamlines the installation process while maintaining safety and environmental compliance. Nonetheless, challenges such as fatigue loading during long-distance towing, optimal pile geometry, and selection of towing paths require further investigation. In conclusion, the finite element framework developed in this study provides a reliable, validated tool for assessing and optimizing the wet-towing transportation of large OWT support structures. The work contributes a valuable computational methodology for engineers aiming to design safer and more efficient marine operations in the rapidly evolving offshore wind energy sector.

Keywords: Offshore wind turbine, Suction pile, Finite element method, Wet-towing, Air pressure stiffness, Structural dynamics, Marine transportation