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# Centrifuge Modeling of Cyclic Degradation of Axially Loaded Piles in Sand for Offshore Wind Turbine Structures

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**A centrifuge test program was designed to explore the influence of repeated cyclic loading on axial performance of pile foundations for jacket structures of offshore wind turbine systems. The program focused on low-amplitude, high-cycle (e.g., 10,000 to 100,000 cycles) loads meant to emulate conditions imposed during operation. The goals of this paper are to (1) demonstrate the feasibility of using a small centrifuge for this application, (2) present an initial data set from scaled centrifuge testing of piles subjected to one-way (tension) and two-way (tension and compression) cyclic axial loading, (3) evaluate the data set within an interaction diagram framework, and (4) provide guidance on implications of the findings and recommended next steps. Observations of the degradation of stiffness, the number of loading cycles to failure, and the evolution of the soil-pile interface friction at different depths are described.**

## INTRODUCTION

Understanding the influence of the soil-pile interface is critical for reliable operations of offshore wind turbine structures (OWTS). The foundation and support structure for an OWTS must satisfy criteria, including limits on stiffness, displacement, tilt, and other characteristics that can influence the system behavior. These requirements are particularly challenging for OWTS because of their complex dynamic loading conditions. The influence of cyclic loading on multipiled support structures represents a major gap in the current state of the practice for offshore wind. These structures involve unique design challenges as a result of (1) the potential for complete load reversal within the piles because of the relatively low gravity loads in the system, (2) the potential for support structures and foundations to be loaded near peak demand during normal operation (i.e., the operating wind load may generate a mudline overturning moment close to, or in some cases greater than during, the design storm condition), and (3) the substantial number of load cycles that occur as a result of the almost continuous operation of the rotor.

Significant degradation in the soil-pile resistance could lead to excessive deformation, or tilt, of the system, thereby rendering the turbine inoperable. Degradation could also result in a reduction of the stiffness of the system, which could reduce the natural frequencies potentially toward resonance with rotor frequencies. For monopile-supported OWTS, lateral loads on the piles are controlling; however, for multipile foundations (e.g., jacket structures), axial loading is often the controlling load transfer mechanism. This paper is focused on the topic of cyclic axial behavior of OWTS piles.

There is a substantial amount of recent testing generated to study the cyclic axial performance of piles in sands, including field tests of steel pipe piles (Jardine and Standing, 2000, 2012), chamber tests using the mini Imperial College Pile (Tsuha et al., 2012, 2015; Jardine et al., 2013), centrifuge tests on model piles (Lehane et al., 2005; Li et al., 2012; Blanc et al., 2015; Isorna et al., 2016), interface shear (element) tests (DeJong et al., 2006; Thomassen et al., 2016, 2017), and numerical and empirical procedures (Seidel and Uriona, 2011; Stuyts et al., 2012; Achmus et al., 2015, 2017; Zheng and Kutter, 2017). Much has been learned from the above-cited works, however, they typically applied $10^3$ or fewer cycles in their experiments, whereas OWTS are typically subject to more than $10^6$ rotor cycles. The discrepancy in the number of cycles makes it difficult to extrapolate with complete confidence the previous results to offshore conditions.

The centrifuge program presented here addresses a critical gap in the design and analysis of OWTS supported by jacket and tripod structures. Specifically, the program was designed to advance the state of the art for understanding the influence of repeated cyclic loading on axial stability of these types of foundations within an offshore wind loading environment by

1. demonstrating the potential for obtaining meaningful results using a centrifuge to measure and evaluate changes in strength, stiffness, and load transfer of a single pile subjected to a combination of low-amplitude, high-cycle count (i.e., up to 100,000 cycles) loads associated with operation and large-amplitude, low-cycle count loads associated with storm loading;
2. developing an initial data set from scale centrifuge testing of piles subjected to one-way (tension) and two-way (tension and compression) cyclic axial loading;

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