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Deformation mechanisms for offshore monopile foundations accounting for cyclic mobility effects

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ABSTRACT

There has been a huge surge in the construction of marine facilities (e.g., wind turbines) in Europe, despite the many unknowns regarding their long-term performance. This paper presents a new framework for design strategy based on performance measures for cyclic horizontally loaded monopile foundations located in saturated and dry dense sand, by considering pile deformations and pore pressure accumulation effects. A three-dimensional finite element model was developed to investigate the behavior of large-diameter piles. The model accounts for nonlinear dynamic interactions in offshore platforms under harsh combined moment and horizontal environmental loads, with emphasis on the cyclic mobility of the surrounding cohesionless subsoil and associated shear. The maximum moment applied in the cyclic analyses is varied from 18% to 47% of the ultimate resistance. The considered data reflect behavior at the expected load amplitudes and cycle numbers during the service life of operation. For low numbers of load cycles (< 1000 cycles), there were no differences between the power law and logarithmic approaches in terms of describing the accumulated deformations; however, for high numbers of cycles (< 10,000 cycles), the logarithmic law was less suited to describe the accumulation response. Magnitude of cyclic loads was found to cause a linear increase in the accumulated rotation. The results from short-term and long-term dynamic response of monopiles indicate that few load cycles with higher load levels are the main concerns in accumulation of pile rotation rather than thousands of load cycles with low amplitudes.

1. Introduction

The design and analysis of foundations for offshore turbines are challenging endeavors, due to the harsh environmental conditions that these structures experience. Recently, such structures have been developed extensively in Europe (e.g., see [27,2,4–7,29,22,23,24,9,15,28]). Foundation concepts that are frequently used for offshore wind turbines include monopiles, jackets, and tension-leg floating substructures. [15] described a state-of-the-art in foundation design for offshore platforms. Under suitable soil conditions, monopiles have shown to be feasible in water depths of up to 35 m.

Due to their slender nature, offshore wind turbines are dynamically sensitive when used under adverse environmental conditions. During the lifetime of a wind turbine, a monopile foundation may be subjected to either a small number of lateral load cycles with large amplitudes, as a result of severe earthquakes or storms, or to regular of lateral load cycles with intermediate amplitudes, due to wave loading in the fatigue and serviceability limit states (FLS and SLS, respectively) [44,50]. In the literature, analytical approaches (e.g., subgrade reaction methods) and finite-element (FE) techniques have been widely used to determine the response of offshore piles to lateral loading.

The p-y curve is a subgrade reaction technique derived from large-scale testing on two flexible, slender piles, according to the design standards [3] and [13]. Both standards recommend the p-y curves initially formulated by [41] and [36]. The p-y methodology is not based on rational mechanics, and material parameters are typically chosen empirically, through observations of pile behavior. Several factors (e.g., diameter and soil-pile stiffness) are not addressed in this methodology, which can lead to severe restrictions. Applying design standards for stiff offshore piles to wind turbines with a slenderness ratio less than 10 is not within the verified range of these standards.

Many authors have provided long-term performance predictions and observations for monopiles. [31] was among the first to address the issue of accumulated rotation and stiffness changes for small-scale stiff

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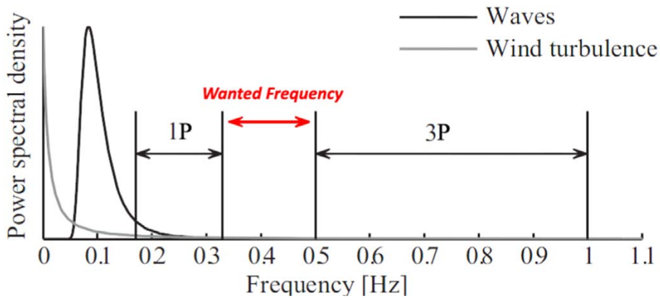

Fig. 1. Frequencies distribution for a fully operational Vestas 4.5 MW wind turbine [30].

Table 1
Pile characteristics.

Parameters	Symbol	Values
Total length	L_t	20, 30, 40, 60 m
Embedded depth	L	20, 30 m
Outer diameter	D	7.5 m
Pile wall thickness	t_p	0.09 m
Equivalent diameter	D_e	4.1 m
Young's modulus	E	2.1×10^8 kPa
Moment of inertia Young's modulus	I	14.84 m^4
Bending stiffness	EI	3.12×10^9 kN m^2

piles after long-term cyclic loading between 8000 and 60,000 load cycles. They thoroughly investigated the dependence of accumulated rotation on relative density, which they found to be very sensitive to cyclic load characteristics. [49] developed and implemented a fully coupled, two-phase, three-dimensional (3D) FE model for explicitly describing the accumulation of water pressure close to the monopile as a function of the number of cycles. [26] and [11] described the change in the bedding resistance in subgrade reaction methods with the number of load cycles.

1.1. Aim and scope of the paper

Although several authors have performed small-scale 1-g tests [31,39,40,44], the applicability of the proposed observations to the design of full-scale monopiles remains questionable. In particular, the stress distribution in a 1-g experiment is not identical to that in the full-scale condition. On the other hand, although values can be scaled in centrifuge experiments conducted at Ng and at the correct stress level corresponding to the full-scale prototype, scaling to prototype is still a difficult task, especially for cyclic tests and limitations exist [26].

This article describes a numerical model for predicting the accumulated pile rotation under one-way cyclic and transient lateral loading, as well as applications to investigate stress paths and soil-pile interactions. The full-scale numerical simulations reported in this paper offer promising predictions for the salient features of soil behavior that were previously not accounted for offshore monopiles. This paper complements previous studies in the field by presenting a series of parametric studies of the developed model predictions.

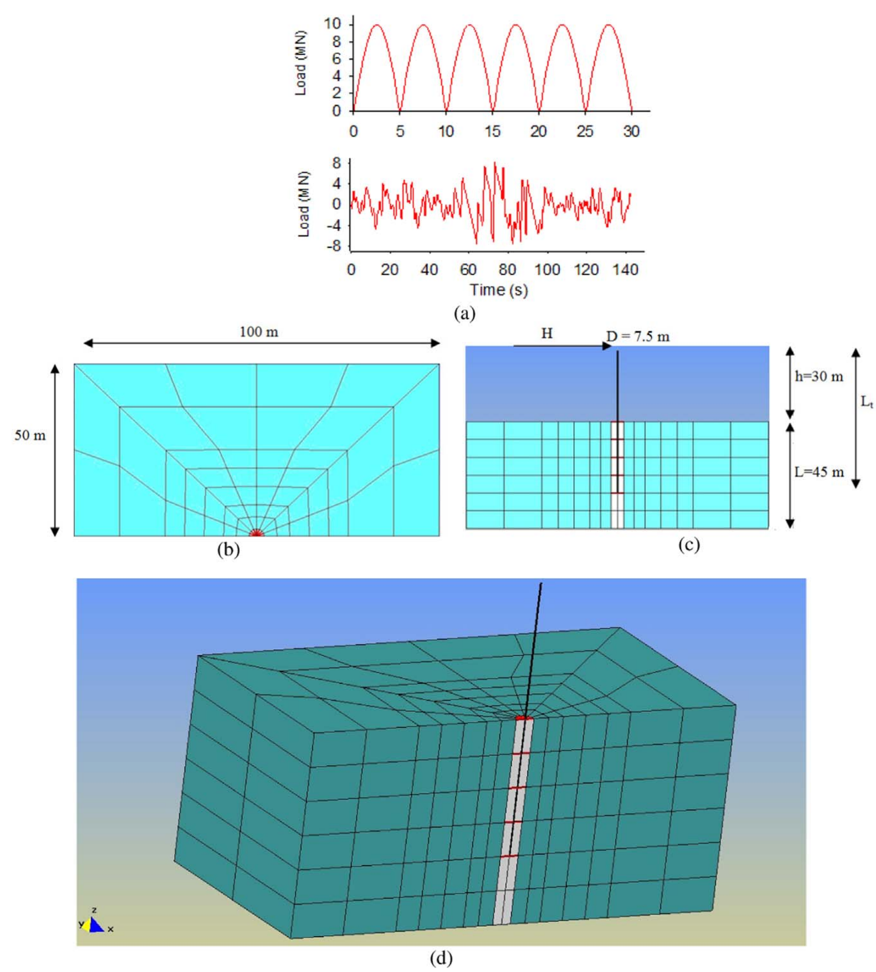

Fig. 2. Typical FE mesh of the developed numerical model: schematic illustration in dense sand subjected to the one-way and transient loading: (a) typical load time histories showing sinusoidal loading and an extreme event (b) plan view (c) side view (d) three dimensional view of Finite Element mesh.