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Research Paper

Behavior of cyclically loaded monopile foundations for offshore wind turbines in heterogeneous sands

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ABSTRACT

This paper presents a probabilistic assessment of the long term performance of monopile foundations for offshore wind turbines in dense sand with spatially varying stiffness. Response of the monopile foundation to long term cyclic loading is simulated by coupling a three-dimensional finite element pile–soil model with a stiffness degradation material model. With the implementation of random field model of sand stiffness variability, this study provides a discussion on the probabilistic effects in the long term response of the pile–soil system. The probabilistic response is evaluated with respect to the serviceability and ultimate limit states of monopile foundations in the Monte Carlo framework for a set of monopile embedment lengths and lateral loading cycles. The statistics associated with the monopile displacements, rotations and bending moments demonstrate the influence of the monopile embedment length and the number of lateral loading cycles on the long term probabilistic response of monopile foundations. The estimated probabilities of exceeding the limit states revealed the serviceability limit state as being dominant in this study and indicated the importance of the installation tolerance on the long term response of monopile foundations.

1. Introduction

Instabilities in oil prices and increasing energy demand initiated the sustainable development policy across Europe [1]. The sustainable development policy promotes a gradual transition from conventional energy sources (e.g., coal, oil) towards renewable energy sources (e.g., wind, hydro power). One of the renewable energy sources intensively developed in the last few decades is wind energy. The wind technology, as a potential clean alternative is gradually moving from onshore to offshore due to several advantages of the offshore wind technology over the onshore counterpart [2]. These include stronger winds, bigger wind turbine size and more available areas for the installation. On the other hand, the offshore environment introduces new challenges (e.g., higher investments in towers and foundations, maintenance issues) that are currently not optimally solved from the technical–economic standpoint [2,3].

The component of interest in this study is the foundation system of the bottom-fixed offshore wind turbines which is currently facing the challenges of reducing cost. Although there are several foundation types developed for the bottom-fixed offshore wind turbines [2] such as; gravity based, monopile, suction bucket and jacket foundation, the monopile is currently dominantly used [4]. The monopile foundation consists of a single large diameter hollow steel pile driven into soil. The pile provides both axial and lateral stability to the wind turbine. Monopile foundations are optimal for water depths from 0 to 25 m [5].

The design procedures for monopile foundations are based on the experience gained from the oil and gas industry, where the American Petroleum Institute (API) method [6] is often used to simulate the response of laterally loaded pile foundations. The API method is a semi-empirical approach included in the recommended practice of several offshore wind turbine design codes [5,6]. The method is based on the Winkler's beam on elastic foundation theory [7], where the response of the soil is simulated by a series of elastic springs. In the API formulation, the mechanical behavior of springs is nonlinear and defined by p–y curves [8,9]. The p–y curves define the nonlinear relationship between the lateral displacement of the pile, y, and the soil reaction, p. The p–y formulation was developed by backcalculating a series of field test on various soil types in both drained and undrained situations for static and cyclic loading conditions [8,9].

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The applicability of the API model to simulate the response of monopile foundations is a subject of discussion [10,11], with issues arising from the absence of continuum effects (e.g., spring coupling) in the Winkler's beam theory and the assumptions introduced in the derivation of the p–y curves. Some of these issues can be avoided by formulating a 3D finite element (FE) [12] or finite difference (FD) model [13] of the pile–soil system [10,11,13]. The 3D model encompasses the continuum effects associated with the response of the monopile foundation [13], while material models can be implemented to simulate the response of the soil volume to static and/or cyclic stress alterations [14–16]. Material models simulating the long term cyclic soil response are commonly grouped in two formulations; explicit and implicit [17]. Explicit formulations simulate the soil response for a given number of cycles from an explicit expression, while implicit models simulate the soil response cycle by cycle [17]. Explicit formulations are preferred in the case of wind turbine foundations, where the soil response is simulated for hundreds or thousands of loading cycles. For this range of loading cycles, implicitly formulated models commonly suffer from the accumulated systematic numerical errors [16,17]. This study implements an explicitly formulated stiffness degradation material (SDM) model [12].

A common design procedure for monopile foundations is based on the safety factor approach [5]. The approach stems from a semi-probabilistic design philosophy where the uncertainties about the design parameters (e.g., soil properties, loads) are controlled by safety factors. The main concern behind the safety factor approach is that it does not provide much physical insight into the likelihood of a design failure as a probabilistic measure [18]. An alternative to the safety factor approach is reliability based design [18–20]. Reliability based design is a probabilistic framework which quantifies uncertainties in design parameters to produce a design with an acceptably small failure probability [19]. This approach is advocated for cases of standardized structural designs e.g., monopile foundations [3]. For example, Legian [21] coupled the variability of soil properties with the API model to evaluate the uncertainties of estimated pile deflections and bending moments. Folse [22] implemented a design point framework to evaluate the effect of uncertainties in several design parameters (including loads and soil properties) on the performance of pile foundations. Later developments led to the implementations of stochastic models of soil variability by means of random fields. In Chan and Low [23], and Tandjira et al. [24], a probabilistic assessment of the pile response is conducted by implementing one-dimensional random field and the response surface method, while in Chan and Low [25] the response surface is augmented with the neural network model. Andersen et al. [26] conducted a probabilistic assessment of natural frequencies of wind turbines by modeling variability of undrained shear strength of clay using a one-dimensional random field. Haldar and Babu [27] implemented a two-dimensional random field to evaluate the effects of spatial variability of undrained shear strength of clay on the response of laterally loaded piles.

This paper presents a probabilistic assessment of long term cyclic behavior of laterally loaded monopile foundations. Probabilistic assessment is conducted by evaluating the effect of sand stiffness variability on the ultimate and serviceability limit states [5]. Response of the monopile foundations to long term cyclic loading in terms of pile displacements, rotations, and bending moments is simulated by a 3D FE pile–soil model coupled with SDM model [12]. Probabilistic assessment is performed in the Monte Carlo (MC) framework for several design cases to evaluate the effects of embedment length and the number of lateral loading cycles on the long term monopile response.

2. Soil-structure interaction model

2.1. Pile–soil model

This study implements a 3D FE model with an elasto-plastic material model to simulate the response of monopile foundations to long term cyclic loading. The 3D FE model is preferred over the API model [5,6] since it can model several characteristic stress–strain zones associated with the response of monopile foundations [28]. Fig. 1 presents a schematic interpretation of the stress–strain zones characteristic of the response of monopile foundations [28]. A passive conical shaped soil zone is formed in front of the pile in the direction of the applied lateral load. Soil in the passive zone experiences an increase in horizontal stresses while it is being pushed forwards and upwards in the direction of the lateral load. As the pile is laterally pushed, a decrease in horizontal stresses occurs in the active conical shaped zone in the back of the pile (i.e., in the opposite direction to the load). As a result of the decrease in horizontal stresses, gapping and sliding between the monopile and the active soil zone can occur. Below the active and passive zones, the deformation patterns of soil indicate behavior analogous to soil flowing around the monopile. The rotational zone, below the flow-around zone is related to the behavior of soil at the tip of the monopile foundation. This zone usually represents a region of small displacements around the rotational center of the monopile.

The geometry of the FE pile–soil model is selected by taking into account the future developments of the offshore wind industry. By the end of 2013, the majority of the operating wind turbines have a power output of up to 3.6 MW [4]. Approximately two thirds of the installed wind turbines are based on monopile foundations, with a diameter ranging from 3.0 to 6.0 m [4]. Future development of wind turbines with a power output up to 8.0 MW will results in more rigorous performance requirements for the foundations in terms of ultimate and serviceability limit states. In the case of monopile foundations, these requirements are met by increasing the embedment pile length, pile wall thickness and pile diameter.

In the context of the future development of the wind turbine technology, this study models a monopile with a diameter of $D = 7.5$ m, a pile wall thickness of $t = 0.09$ m for embedment lengths of $L = 30$ and $L = 40$ m. The monopile is loaded with a vertical load of $V = 10$ MN, representing the weight of the upper part of the wind turbine. The combined wind and wave actions on the

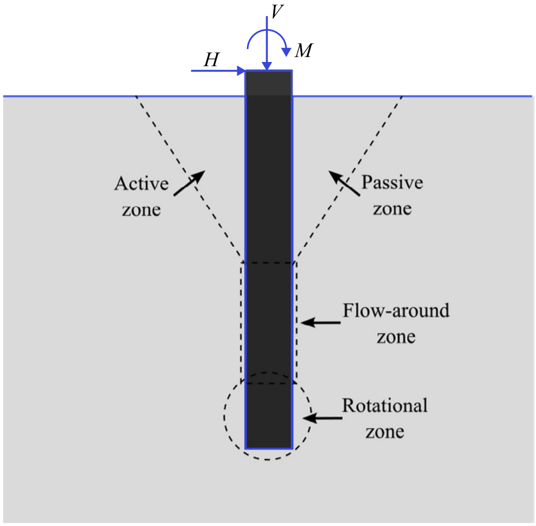

Fig. 1. Characteristic soil response zones associated with laterally loaded piles.