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Assessment of the dynamic behaviour of saturated soil subjected to cyclic loading from offshore monopile wind turbine foundations

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ABSTRACT

The fatigue life of offshore wind turbines strongly depends on the dynamic behaviour of the structures including the underlying soil. To diminish dynamic amplification and avoid resonance, the eigenfrequency related to the lowest eigenmode of the wind turbine should not coalesce with excitation frequencies related to strong wind, wave and ice loading. Typically, lateral response of monopile foundations is analysed using a beam on a nonlinear Winkler foundation model with soil–pile interaction recommended by the design regulations. However, as it will be shown in this paper, the guideline approaches consequently underestimate the eigenfrequency compared to full-scale measurements. This discrepancy leads the authors to investigate the influence of pore water pressure by utilising a numerical approach and consider the soil medium as a two-phase system consisting of a solid skeleton and a single pore fluid. In the paper, free vibration tests are analysed to evaluate the eigenfrequencies of offshore monopile wind turbine foundations. Since the stiffness of foundation and subsoil strongly affects the modal parameters, the stiffness of saturated soil due to pore water flow generated by cyclic motion of monopiles is investigated using the concept of a Kelvin model. It is found that the permeability of the subsoil has strong influence on the stiffness of the wind turbine that may to some extent explain deviations between experimental and computational eigenfrequencies.

1. Introduction

For offshore wind turbines, the monopile foundation concept, in which a pile made of welded steel is driven open-ended into the soil, is often applied. For a variety of subsoil conditions, this type of foundation has proven to be cost-effective at shallow water. As an example, the Thanet and Bligh Bank wind farm consist of 3.0 MW turbines installed on monopile foundations in water depths between 15 and 30 m. As future offshore wind turbines with rated power values of 5–6 MW installed on monopile foundations are expected to be installed at greater water depths, the dynamic system response becomes highly sensitive to excitations with low frequency content.

Besides the static bearing capacity of wind turbines, the fatigue limit state is of paramount importance to investigate. To reduce the fatigue damage accumulation during the lifetime of wind turbine structures, amplification of the response must be avoided. In this regard, sufficient system stiffness is required to ensure that the eigenfrequency f_1 related to the lowest eigenmode $\boldsymbol{\Phi}^{(1)}$ of the wind turbine structure does not coalesce with excitations from the operation frequency of a three-blade turbine and waves. Fig. 1 illustrates the realistic spectra representing aerodynamic and hydrodynamic excitation for the North Sea and the excitation ranges 1P and 3P associated with the mass imbalances in the blades and shadowing effect from the wind each time a blade passes the tower, respectively. The forcing frequency 1P is the frequency of the rotor revolution and the 3P frequency is the frequency of blades passing the tower on a three-bladed turbine. The mass imbalance can be due to differences in the blade weight during installation or cracking in a blade where moisture finds its way. Three possible designs can be chosen for a wind turbine [2]: a very stiff structure with the eigenfrequency f_1 above 3P ("stiff–stiff"), the eigenfrequency f_1 in the range between 1P and 3P ("soft-stiff") or a very soft structure with the eigenfrequency f_1 below 1P ("soft–soft"). A "soft-stiff" wind turbine structure is often chosen in current practice because a huge amount of steel is required for a "stiff–stiff" structure. As the trend is to create larger turbines, rotor blades become longer, generator masses greater and hub heights higher. Thus, the rotation frequency and the first natural frequency will decrease. It may then seem impossible to

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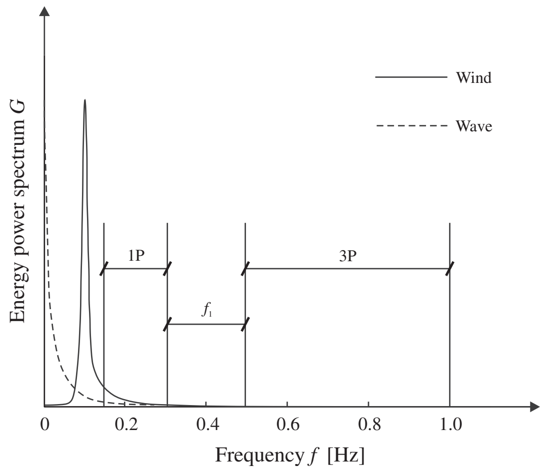

Fig. 1. Excitation range for a modern offshore three-bladed wind turbine structure [1].

design wind turbine structures as "soft–soft" structures, since the risk of the hydrodynamic frequency range falls into 1P is relatively high. Finally, it should be noted that ice breaking [3,4] can induce serve vibrations of offshore wind turbines with excitation frequencies close to the structural eigenfrequencies of offshore wind turbines. Evidently, this effect should only be considered relevant for wind turbines installed in cold regions.

The eigenfrequency f_1 depends on the stiffness of the foundation and tower as well as on the stiffness of the interaction between soil and foundation. In general, the stiffness of the soil–structure interaction is complicated to determine, since cyclic loading might lead to possible softening/hardening of the soil. Kausel [5] made an extensive review of some of the leading developments for solving soil–structure interaction problems. In this regard, finite element models are high-precision methods in simulation of soil–pile interaction problems. Klar and Frydman [6] presented 3-D models and Winkler models based on the commercial two-dimensional finite difference code FLAC under static, seismic, and lateral dynamic loading. In addition, Yegian and Wright [7], Randolph [8], Trochanis et al. [9] and Achmus et al. [10] used the finite element method (FEM) for analysing the dynamic response of pile-supported structures. Al-Wakel et al. [11] implemented a frequency-dependent damping model by using a 3-D FE model, where the saturated soil was subjected to cyclic and harmonic forces. Medina et al. [12] analysed the effect of the soil–structure interaction on the dynamic behaviour of piles. Impedances and kinematic interaction factors of the pile configurations were calculated using a coupled boundary-element/finite-element methodology.

However, since the FEM comes at the cost of great computation times, a beam on nonlinear Winkler foundation (BNWF) model, originally formulated by Winkler [13], is usually employed for design of monopile foundations due to its versatility and efficiency. The pile is modelled as a beam on a nonlinear foundation in which the interaction between pile and soil is modelled as a series of uncoupled springs. The spring stiffness is governed by the so-called p–y curves, where p and y are the resulting force per unit length in the horizontal direction and the corresponding displacement, respectively. Following this approach, Matlock et al. [14], Makris and Gazetas [15] and Nogami et al. [16] analysed the soil–pile interaction for different soil conditions. El Naggar and Novak [17,18] studied the lateral response of monopiles to transient dynamic loading. Based on inner and far field models accounting for the soil nonlinearity and wave propagation away from the pile, reasonable agreement between the developed model and field tests was obtained. Further, El Naggar and Bentley [19] formulated p–y curves for dynamic soil–pile interaction and Kong et al. [20] presented a simplified method including the effect of separation between the pile and the soil. The last-mentioned has further been studied by Memarpour et al. [21], who developed a BNWF model that accounted for gap formations between pile and soil. Experimental investigations of the interaction between foundation and subsoil have been reported by Bhattacharya and Adhikari [22] and Lombardi et al. [23]. Based on a series of 1-g laboratory tests of a scaled wind turbine on a monopile foundation for different soil conditions, the eigenfrequency related to the lowest eigenmode was evaluated and successfully compared with BNWF models. Sørensen and Ibsen [24] and Damgaard et al. [25] used BNWF models to demonstrate the correlation between scour depths and eigenfrequencies of offshore wind turbines, whereas Barakat et al. [26], Low et al. [27], Fenton and Griffiths [28] and Andersen et al. [29] applied BNWF models for reliability-based soil–pile interaction. A further development of BNWF models for nonlinear dynamic soil–pile interaction was conducted by Allotey and El Naggar [30].

Several formulations of p–y curves exist for sand and clay. Originally, the formulations were developed as a consequence of the oil and gas industry's expansion of offshore platforms, where the soil–pile interaction became crucial to analyse. Design regulations such as API [31] and DNV [32] have adopted the p–y curve formulation for sand proposed by Murchison and O'Neil [33] based on the field tests presented by Cox et al. [34]. For soft and stiff clay, the p–y curve formulations recommended by the design regulations are based on the work performed by Matlock [35], Reese and Welch [36] and Dunnavant and O'Neill [37]. Overall, the p–y curve formulations are based on a number of field tests on fully instrumented flexible piles with significantly smaller slenderness ratio compared to offshore wind turbine foundations. Several assumptions of the derivations of the formulations can be questioned. In the authors' opinion, the most important ones are listed below:

- The soil is not treated as a continuum but as a series of discrete, uncoupled resistances. As a consequence, there is no rigorous description of 3-D failure and deformation mechanisms in the soil surrounding the pile.
- Using the BNWF model, the pile bending stiffness is employed when solving the governing equation. However, the spring stiffness representing the soil stiffness is independent on the pile properties, which is questionable.
- The p–y curve formulations were originally developed and verified for flexible piles with diameters up to 2 m. However, for offshore wind turbines, monopiles with diameters of 4–6 m exist. Hence, a pile which behaves rigidly will have a negative deflection at the pile toe. This deflection causes shearing stresses at the pile toe, which increase the total lateral resistance. In addition, rotations at the pile toe will provide a moment on the pile caused by vertical stresses acting on the pile toe, see Fig. 2. These effects are neglected in the p–y curve formulations.
- The p–y curve formulations are based on full-scale tests on piles installed in rather homogenous soil. However, piles are often installed in a stratum.
- The initial stiffness of the p–y curves is independent of the pile diameter. Sørensen et al. [38] provided an expression for the initial stiffness of sand that depended on the depth below soil surface, the pile diameter and Young's modulus of elasticity of the soil. Validated against laboratory tests, it was found that the initial stiffness of the p–y curves highly depends on the pile diameter.

As it will be shown in this paper, a BNWF model based on the incorporated p–y curves recommended by the design regulations