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Dynamic analysis of offshore wind turbine in clay considering soil–monopile–tower interaction

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ABSTRACT

A comprehensive study is performed on the dynamic behavior of offshore wind turbine (OWT) structure supported on monopile foundation in clay. The system is modeled using a beam on nonlinear Winkler foundation model. Soil resistance is modeled using American Petroleum Institute based cyclic *p*–*y* and *t*–*z* curves. Dynamic analysis is carried out in time domain using finite element method considering wind and wave loads. Several parameters, such as soil–monopile–tower interaction, rotor and wave frequencies, wind and wave loading parameters, and length, diameter and thickness of monopile affecting the dynamic characteristics of OWT system and the responses are investigated. The study shows soil–monopile–tower interaction increases response of tower and monopile. Soil nonlinearity increases the system response at higher wind speed. Rotor frequency is found to have dominant role than blade passing frequency and wave frequency. Magnitude of wave load is important for design rather than resonance from wave frequency.

1. Introduction

Monopile is a common choice as foundation for offshore wind turbines, as this type of foundation has proved to be economical at shallow water depth [1–5,34]. Monopile is a long single slender steel member, typically 3–6 m outer diameter, 22–40 m long, and is installed at a water depth of 10–25 m [6]. Monopile foundations support slender flexible tower and withstand complex aerodynamic and hydrodynamic loads due to wind and ocean wave [7]. Therefore, stability and dynamic response of the monopile–tower system are of great significance to an OWT system in the context of the current design paradigm [8–11].

In order to reduce the cost, modern OWT is comprised of powerful generator and overall weight of the system is minimized [12,13]. This in turn makes the structure more sensitive to dynamic loading even at low frequencies [14,38]. Modern OWT system is integrated with a variable speed generator, hence the operational speed of the rotor (or 1P frequency) varies from 10 to 20 rpm, i.e., excitation frequency interval is about 0.1–0.3 Hz [17,1]. Furthermore, blade passing frequency (i.e. 3P frequency for 3 bladed OWT) induces dynamic load on the structure due to tower shadowing effect [23]. Possible frequency range of ocean wave varies between 0.04 and 0.1 Hz [18]. A typical frequency range of energy rich waves is from 0.05 to 0.5 Hz [19]. Therefore, the first natural frequency of the system must be separated from the excitation frequencies of wind and wave loading to avoid dynamic amplification of response and early fatigue damage [24,34].

Several research studies on monopile foundation have been performed [25–28,19,29]. In all these studies, the superstructure was not accounted for the analysis. However, estimation of the natural frequency and responses of the structure including foundation and subsoil is essential, since soil–monopile–tower interaction changes the system responses significantly [12]. This apart, the serviceability criteria (SLS) for monopile (maximum 0.5° rotation at seabed level, [20]) and tower (maximum 5° rotation at tower top, [30]) are different. This means that structure and foundation interaction must be treated jointly in order to check stability of a flexible OWT system. A few other research studies incorporated superstructure in their analysis, however the foundation is replaced by linear springs e.g. [31,1,32,16]. Major drawbacks of this simplified model are associated with the determination of appropriate foundation stiffness values and incorporation of soil nonlinearity in soil–monopile–tower interaction [23,33]. Current design approaches are mostly relying on quasi-static load on the structure [27,34,41]. However, response of a structure subjected to a dynamic wind loading is significantly affected by soil structure interaction [57]. Hence, a dynamic analysis of a coupled wind turbine and foundation system under combined wind and wave loading is indeed necessary for rational design [58,59]. In general, resonance condition is avoided for OWT structure and it is

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achieved keeping the fundamental frequency of the system ±10% away from the 1P and 3P frequencies [36]. For variable speed OWT, the possibility of occurrence of resonance condition is more due to wide ranges of rotor and wave excitation frequencies [23,37]. Furthermore, the fundamental frequency of a system may deviate from the estimated value due to uncertainties in soil condition, installation particularities and stiffness degradation of soil [1,32]. Therefore, instead of relying on resonance avoidance strategy, a comprehensive dynamic analysis needs to be carried out incorporating all possible forcing mechanisms [37].

Research studies on the dynamic interaction of OWT taking into account soil–monopile–tower interaction are rather limited in number. Andersen et al. [34] studied effects of soil uncertainty on the first natural frequency and response of an OWT including monopile foundation in clay using a beam on nonlinear Winkler foundation model. Nonlinear cyclic *p–y* curves as suggested in API [35] were used in their model. However, dynamic analysis was not accounted for the analysis. Cyclic response of a monopile foundation in sandy soil was carried out by Achmus et al. [27] using a three-dimensional finite element analysis. In their analysis, a stiffness degradation model was incorporated and effects of pile length, diameter and loading state on the lateral deformation of monopile were investigated without taking into consideration of tower interaction and dynamic analysis. Lombardi et al. [1] carried out a series of laboratory tests on model OWT supported on a monopile subjected to cyclic load. Effect of foundation flexibility, number of load cycles and load amplitude on the natural frequency of the system were examined, however, various soil, monopile, tower and loading parameters that affects the dynamic responses of an OWT system were not addressed. Various foundation modeling techniques to assess the first natural frequency of OWT were developed by Zaaijer [23]. In order to get new insights, a comprehensive assessment of dynamic behavior of OWT for various structural and soil parameters was suggested.

Currently, OWT foundations are modeled using simple beam on Winkler foundation model using API [35] based *p–y* curves [34,38]. It is worth to mention, API [35] based *p–y* curve under cyclic load is pertinent to the small diameter flexible piles and it overestimates the soil reaction at greater depth and underestimates at the top of large diameter monopiles [1,39,40]. In addition, behavior of clay at low to medium strain level is not accounted for in API [35] based *p–y* curves, which may have an impact on the responses at low load level [58]. The *p–y* curves for cyclic loading are based on field tests conducted for fewer than 200 cycles [27]. No explicit guideline is available in recent design codes to predict the change of the soil stiffness under long term loading – which is an important consideration for serviceability limit state design [1,60]. Despite the limitations of API [35] based *p–y* curves, they are extensively used within the offshore industry [26,34,38,42] and recommended in several design guidelines [20,35,41].

In this paper, monopile supported OWT structure founded in clay is modeled as a beam on non-linear Winkler foundation model. The widely accepted *p–y* method is used to model soil resistance following the API [35] based cyclic *p–y* relationship applicable to piles in clays. Pile shaft and end bearing resistance is modeled using *t–z* and *Q–z* springs [35]. A dynamic analysis in time domain is carried out using finite element model. Aerodynamic damping, structural damping, radiation damping and hydrodynamic damping are considered as a combined form in this study. Objective of this study is to examine the effect of several parameters such as the soil–monopile–tower interaction, lateral soil resistance under cyclic loading, embedded length of monopile, diameter and thickness of monopiles, soil stiffness, tower height, rotor speed, wind velocity, wave frequency, wave height and wave length that affect the dynamic behavior of the overall structure. Incorporation of dynamic effect in the analysis of OWT is also examined comparing the responses obtained from a dynamic analysis in time domain and a static analysis. Effect of

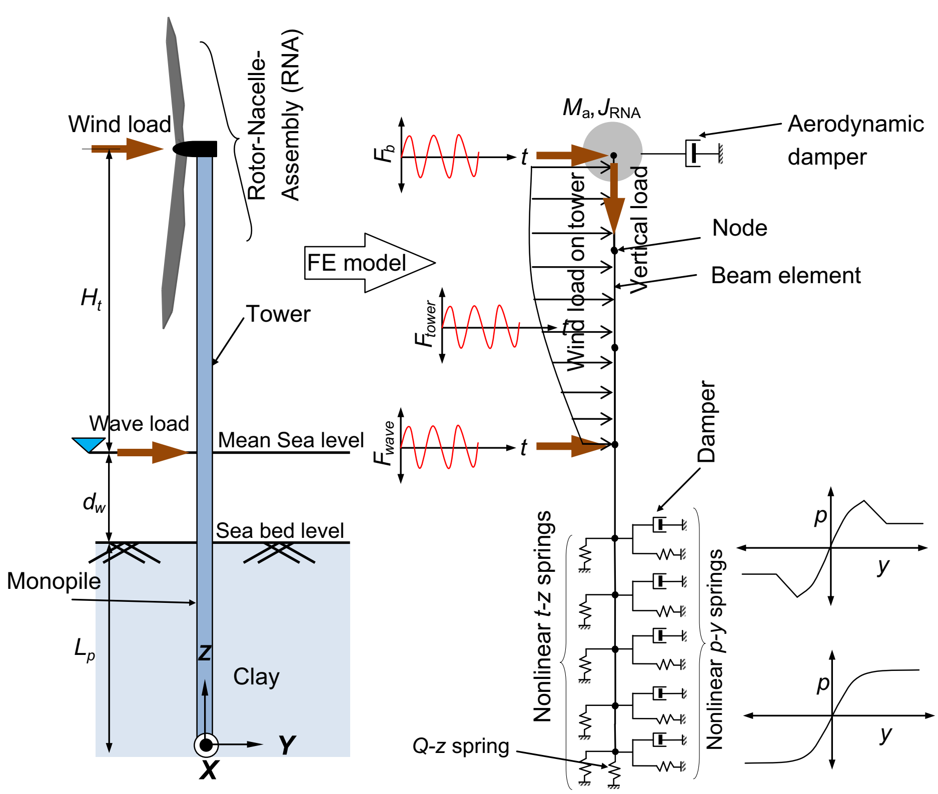

Fig. 1. A monopile supported OWT system in clay and *p–y* analysis.