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Stochastic response of jacket supported offshore wind turbines for varying soil parameters

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ABSTRACT

Wind turbines on jackets are being increasingly installed offshore. This paper attempts to investigate the effect of soil-structure interaction (SSI) on a jacket-offshore wind turbine (OWT) in a water depth of 70 m using JONSWAP spectrum. Stochastic responses of the OWT under varying soil profiles and met-ocean conditions are studied, by coupling the aerodynamic and hydrodynamic forces. From stochastic time domain response analyses, the SSI is observed to have significant influence in soft clay and layered soils at and above rated wind speeds whereas the dense sand have negligible influence.

1. Introduction

Wind turbines are increasingly being installed in offshore deeper waters due to higher wind speeds and lesser visual impact. Additionally, lower turbulence, ease of transportation and abundance of available sites make offshore wind energy an attractive proposition [1]. The design of substructures and foundations for offshore wind turbines (OWTs) are borrowed from the prevailing concepts in the offshore oil and gas industry. However, a proper coupled dynamic analysis is necessary to predict the response and comprehend the modes of failure. As unlike in the case of oil platforms, OWTs may be more flexible and are subjected to high lateral loads, from combined wind, waves and currents, to the tune of 50–150% of the vertical loading [2]. This calls for a detailed analysis of the different loading effects for the OWT structures [3].

One major factor that determines the substructure for offshore wind turbines is the water depth at the installation site. Monopiles till now have been widely used as a support for OWTs in shallow waters (less than 25 m of water depth) and over 75% of the installed OWTs in Europe are on monopiles [4]. However, for deeper water depths within 40–100 m, jackets are usually preferred ones as they are hydrodynamically transparent to wave forces [5]. A detailed review of various substructure concepts of OWTs has been discussed in Ref. [6]. The use of jackets as support structures for OWTs is gaining prominence (*e.g.*, the Alpha Ventus and the Beatrice Demonstrator [7]). Recent studies have also analyzed the response of jacket supported OWTs under the aerodynamic and hydrodynamic loads [8–11]. However, the above studies do not consider soil-structure interaction and assume the jackets are considered to be fixed at the mudline. This exclusion of soil in analysis is a reasonable assumption for 'stiff/rigid' soils whereas the soil effects becomes more important when OWTs are installed in 'softer' marine soils [12] or a combination of loads acts on the structure. Therefore to obtain the response of OWT installations in softer soils, a combined analysis under different loads is necessary to avoid resonance effects.

Based on the experiences in the German industry, a comprehensive review of the prevalent methodologies for the design of the OWT foundation was reported by Ref. [2]. The limitations of the $p-y$ method in offshore design standards [13,14] vis-à-vis offshore industry practices have been reviewed by Ref. [15] and it was concluded that a proper finite element analysis for addressing nonlinearities in soil-behaviour is necessary. A scaled model of 3 MW Vestas V90 OWT was experimentally studied to illustrate the

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effects in kaolin clay under cyclic loading by Ref. [16]. They reported that shear strain of the soil changes considerably and therefore its has a considerable effect on the natural frequency variation. A guideline on the choice of monopile diameters have also been proposed. Another work using shake table experiments to investigate the liquefaction effects on natural frequency and damping on pile supported structures was studied by Ref. [17]. They found that natural frequencies changed considerably due to seismic liquefaction. The long term effects of cyclic loading on piles supporting OWT was evaluated by Ref. [18] and they concluded that cyclic loading increased stiffness contrary to degradation. To study the effect of the soil flexibility of wind turbines, an experimental model was developed by Ref. [19]. The results are then validated by modelling the wind turbine as a Euler Bernoulli beam using a finite element framework. The complete wind turbine is modelled as a beam with one end being supported by translational and rotational spring (soil model) while the other end of the beam having a lumped mass (rotor-nacelle-assembly model). These authors also derived an expression in another work [20] to obtain the natural frequency of the wind turbine structure. This closed-form expression included the properties of soil as parameters. Studies on effect of shear strain on natural frequencies were experimentally analyzed for three different footings – symmetric tetrapod, monopile and asymmetric tripod on suction caissons by Refs. [21,22]. All the above studies are using monopiles to study effect on natural frequencies and the OWT response did not consider the combined effect of aerodynamic and hydrodynamic loads along with the soil.

There are also few attempts in literature, wherein, the effect of wind and wave loads on the response of OWTs on framed structures (*i.e.*, jackets) along with soil effects have been investigated. The effects of soil-structure interaction ('hard' soil *i.e.*, interface friction angle greater than 35°) using fixed-base method, the $p-y$ method and the pile group effect was studied by Ref. [23] to understand the performance of braces in jacket OWTs. Seismic studies on jacket OWTs have been conducted by Ref. [24] to understand their effects on overall performance during the earthquakes. There also exist some studies only for jacket structures without the wind turbine. One example is the parametric study on the response of jacket structure subjected to transient loading under extreme waves by Ref. [25]. Though there have been studies where the loading effects of OWT have been studied separately, however a combined aerodynamic, hydrodynamic and geotechnical analysis for OWTs is necessary. As offshore farms can be located where varying soil conditions are present, a parametric analysis under operational and parked conditions using various soil parameters is also important.

In this paper, the response of the jacket supported NREL 5 MW OWT [26] for various soil profiles is analyzed. The OWT response (tower top displacement and forces at the jacket-base) are studied keeping in mind that the serviceability limit state criteria (displacements) is satisfied. Each soil profile is studied under different sea-state condition (wind speed, significant wave height and peak spectral period) as per the JONSWAP spectrum. The sea-states are chosen such that three are in operational regime (below rated, at rated and above rated wind speeds) while one is in idling regime (beyond cut-out wind speed). Soil properties along the pile are modelled using the *p-y*, *t-z* and *Q-z* curves as recommended by modern design standards [13,14]. In this work, these curves are represented through nonlinear springs along the length of the pile. The hydrodynamic loads are modelled using USFOS [27] whereas the aerodynamic loads are obtained using the aerodynamic code FAST [28]. Since the loading becomes stochastic/random due to turbulent wind conditions and irregular (JONSWAP spectrum) waves, the OWT response has to be handled in a random framework. Therefore, 25 Monte Carlo Simulations are carried out in time domain for each case and the response obtained is through ensemble averaging. The paper now runs with additional four sections. The structural, geotechnical and NREL 5 MW OWT [26] models used in the study are detailed in section §2. The section also details the numerical methods. Theoretical background for the combination of aerodynamic and hydrodynamic load calculations is briefly explained in section §3. Section §4 focuses on the research findings of the present study and the paper concludes with section §5. Note that in the paper, the term 'foundation' refers to the piles embedded in the soil, where as the 'substructure' stands for the braced jacket, extending from the transition piece to the pile heads.

2. Model specification

2.1. NREL 5 MW offshore wind turbine

The NREL 5 MW OWT, conceptualized on the REpower 5 MW turbine [26], is considered for the present work. The wind turbine (rotor-nacelle assembly) is placed on a tapering circular steel tower (70 m long) supported on a jacket structure. The tower top (or the yaw-bearing), is located at a height of 88.15 m above the mean sea level (MSL) and the tower outer diameter varies from 5.6 m at the base to 4 m at the top. A transition piece joins the tower with the jacket and this transition piece (of length 4 m) is modelled by means of simple rectangular beam elements. The steel transition piece has a mass of 666 t with density 15.14×10^{3} kg/m^{3} so as to compensate for not including bolts, flanges and welds in the numerical model. The tower and turbine is modelled using the information available in Ref. [29]. The tower model details are reproduced in Table 1. This OWT has been widely used as a benchmark for wind energy studies and its defining features are given in Table 2. It is a 3-bladed, variable speed, pitch controlled turbine with an upwind rotor configuration and is a representative model of the multi-megawatt OWTs.

2.2. Jacket substructure

Jackets are three dimensional space frame structures widely used as offshore oil platforms. The present model is a four-legged structure that is supported through pile foundations. The water depth at the site is 70 m. The jacket structure extends 20 m above the mean sea level (MSL). The jacket has a footprint of 32 m × 32 m at the mudline. Five bays of $X-$ bracings interconnect the main tubular legs while two horizontal $X-$ bracings are placed at 2.5 m and 50 m height above the mudline. Fewer horizontal bracings are required as the top deck and foundation also provide sufficient horizontal rigidity to the structure. The piles are terminated at a depth of 45 m below the mudline and are of 1.8 m in diameter and of wall thickness 4 cm. The jacket is developed using two-noded beam elements.

Table 1
OWT tower dimensions [29].

Design level (m).	Outer diameter (m)	Thickness (mm)
88.15	4.000	30
83.15	4.118	30
74.15	4.329	20
64.15	4.565	22
54.15	4.800	24
42.15	5.082	28
32.15	5.318	30
21.15	5.577	32
20.15	5.600	32