8th International Conference on Asian and Pacific Coasts (APAC 2015)

Dynamic Analysis of an Offshore Wind Turbine Including Soil Effects

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Abstract

Offshore wind turbines (OWTs) offer an attractive, sustainable solution to the impending global energy crisis. A major challenge in fixed-bottom OWT design is accounting for soil-structure interaction (SSI) under the influence of random dynamic loading from wind, waves and currents. Usually, SSI is either ignored in OWT studies or is incorporated by means of simplified foundation concepts like the apparent fixity model. OWTs in shallow water depths (less than 30 m) are mostly supported on monopiles - large diameter steel pipe piles driven into the subsoil. Monopiles transfer the dynamic lateral loads into the soil by bending action. The present work deals with the dynamic analysis of the NREL 5MW OWT on a monopile foundation, in Indian waters. It involves parametric studies on various clayey soil profiles - soft, medium stiff and stiff clay. An operational wind speed of 12 m/s and a sea state of 4 m significant wave height and 10 s spectral peak period are considered. The OWT design should ensure that the natural frequency is away from the forcing frequencies of wind, wave and rotor. A water depth of 20 m is considered. Hub-height aerodynamic loads are obtained using the NREL-FAST code, which is based on the blade-element momentum (BEM) theory. The hydrodynamic time domain analyses are performed in the FEM based coupled hydrodynamic - geotechnical software, DNV-GL - USFOS. USFOS makes use of the JONSWAP spectrum to generate irregular waves. Soil is represented by means of *p-y*, *Q-z* and *t-z* curves. Results indicate the significance of including SSI in OWT studies. Variation in response due to change in pile penetration depth and pile diameter are also highlighted. Stiffness of clay is the design driver for OWTs.

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1. Introduction

Offshore wind turbines are gaining popularity as the need to offset the nonrenewable energy crisis is being recognized. OWTs in shallow waters are usually supported on monopile substructures, which are essentially large diameter piles in the range of 3-6 m. Monopiles transfer lateral loads from wind and waves by bending action, into the soil. Unlike oil and gas structures, OWT systems are subjected to heavy lateral loads, often to the tune of 150% of the vertical loading (Lesny, 2010). This calls for a comprehensive dynamic analysis, especially in soft soils, where the natural frequency of the system could undergo significant variations (Bazeos *et al.*, 2002).

Laterally loaded piles are designed using the $p - y$ method specified by the API (2000). However, these soil curves are derived from experiments involving small diameter piles and their validity for monopile design is still being debated (Achmus and Abdel-Rahman, 2012). Lesny and Wiemann (2005), Haiderali *et al.* (2013), Achmus *et al.* (2009) etc. have made use of quasi-static mudline loads to investigate the response of monopiles. Abhinav and Saha (2015) analysed for a jacket subjected to random wave loads considering soil structure interaction while, Gao *et al.* (2010) showed that jacket structure can be analysed as a set of monopiles of varying diameters. ABS (2011) followed a quasi-aerostatic-hydrodynamic approach to study OWT response under different water depths. Bisoi and Haldar (2014) analyzed a 2MW OWT under dynamic loads, including soil-structure interaction (SSI) Here, the aerodynamic load at the hub was modelled as a function of the rotor frequency.

The present work deals with the analysis of a monopile support structure for the NREL 5MW baseline OWT, under aerodynamic and hydrodynamic loads, for varying soil conditions. The FEM-based code USFOS (SINTEF Group, 2001) is used for hydrodynamic analysis. USFOS implements a nonlinear FE formulation based on Green strain E (valid for all magnitudes of rotation and displacement), where a finite element represents an actual element of the structure. This pre-empts the choice of mesh-size and speeds up computation. The HHT-α method is used for dynamic analysis. Aerodynamic loads are derived using an aeroelastic code, FAST (Jonkman and Buhl, 2005). Three different clayey soil profiles - soft, medium stiff and stiff clay - are considered. The effects of soil stiffness variation, pile penetration depth and pile diameter, on the lateral response and natural frequency of the OWT structure are investigated. Soil stiffness is derived using the soil curves specified by API (2000). Results show significant variations in the response and point towards the need for detailed modelling of soil-structure interaction in the analysis of OWT structures.

2. Numerical modeling

2.1. Structural model

The NREL 5MW baseline OWT, conceptualized by Jonkman *et al.* (2009), is considered in the present study. The numerical model of a monopile supporting the NREL 5MW OWT, in a water depth of 20 m is developed in USFOS. The turbine rotor-nacelle-assembly (RNA) is supported by a steel tower, connected to the monopile through a cylindrical transition piece. The diameter and thickness of the tower varies from 6m and 0.027 m respectively, at the base, to 3.87 m and 0.019 m respectively, at the top. The components of the OWT structure and the corresponding design levels are represented in Figure 1. A higher density value is considered for steel (8500 kg/m³) to account for the absence of bolts, flanges and welds in the model. The monopile has a diameter of 6 m and is founded on uniform stiff clay. Two other soil profiles (medium-stiff clay and soft clay) are also considered for the analysis, to investigate the response of the structure under dynamic loads. The soil profiles are defined in Table 1. Here, γ' is the submerged unit weight, Su is the undrained shear strength and ε_{50} is the strain at 50% of maximum stress in undrained compression test. The depth of embedment is taken as 42m or 7 times the pile diameter. The wall thickness (t) of the monopile is defined by API (2000), on the basis of its diameter (D), as shown in equation 1.
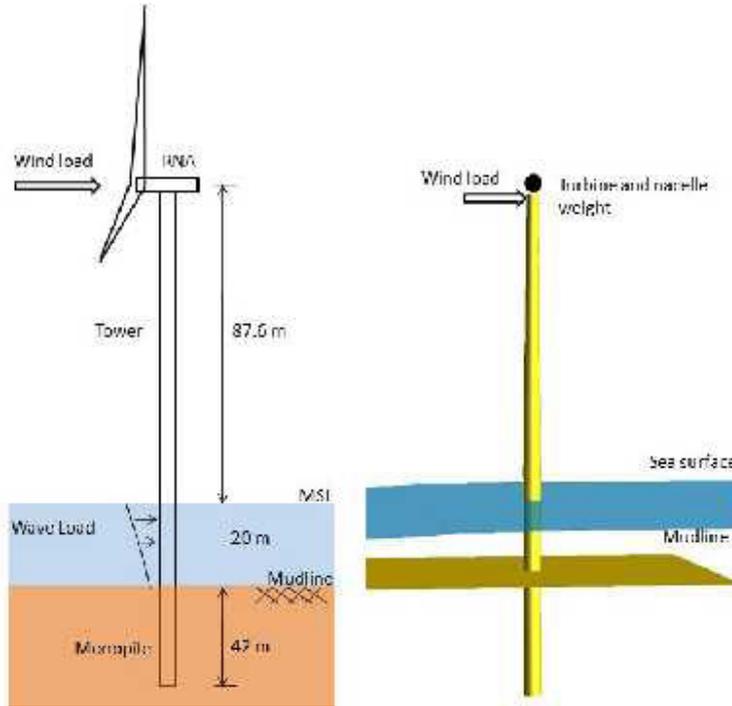
$$t = 6.35 + \frac{D}{100} \qquad (1)$$

Fig. 1. OWT conceptual and FE model

Table 1. Soil profiles

Soil type	γ (kN/m³)	Su (kPa)	ε_{50}
Soft clay	8	40	0.020
Medium stiff clay	8	80	0.010
Stiff clay	8	120	0.005

The tower and piles are modelled using 2-noded beam elements. All analyses are performed for an operational hub-height wind speed of 12 m/s and a sea-state defined by a significant wave height (H_S) of 4 m and wave spectral peak period (T_P) of 10 s.

2.2. Modelling of soil-structure-interaction

Soil-structure interaction is modelled in USFOS using lateral and axial nonlinear spring-to-ground elements along the length of the pile. The properties of the spring elements are derived from the $p - y$, $t - z$, and $Q - z$, curves recommended by API (2000). Pile-soil interaction in the lateral direction is accounted for, by the lateral soil resistance - deflection or $p - y$ curves, while that in the vertical direction is modelled using the curves for skin friction ($t - z$) and end bearing ($Q - z$). More information on the development of cyclic $p - y$ curves for soft and stiff clays is described in Reese and van Impe (2011).

2.3. Modelling parameters

The OWT is located in a water depth of 20 m in clayey soil. The hub height wind speed is 12 m/s. Simulations are performed for duration of 600 s. A time step value of 0.01 s has been used for dynamic analysis. Soil springs are attached to the pile at a distance of 2 m. A frequency value of 300 is used for the discretizing the JONSWAP spectrum by constant area method.

3. Description of loads

OWT are subjected to the action of aerodynamic and hydrodynamic loading. USFOS has coupled hydrodynamic and geotechnical modules. However, the absence of an aerodynamic component requires the use of a separate code for the same. According to Seidel *et al.* (2009) and Gao *et al.* (2010), the response of an OWT can be accurately realized using decoupled analyses, if its natural period varies significantly from the predominant wave period. The fundamental vibration mode of the OWT involves the vibration of the tower, indicating the lack of a significant contribution of wave loading, to this mode. This is consistent with the findings in Gao *et al.* (2010) and points to a lack of strong coupling between wind and wave loads. Hence, a decoupled analysis could be used to model the response of the OWT. The present work ignores the influence of wind loading on the tower of the OWT. The modeling concepts for dynamic loading are discussed below.

3.1. Aerodynamic loads

Aerodynamic loads on the NREL 5MW OWT are computed using the FAST code. NREL's TurbSim code (Jonkman, 2009) is used to generate stochastic wind fields corresponding to a hub-height wind speed of 12 m/s. The Kaimal spectrum (Kaimal *et al.*, 1972) is used in conjunction with the Normal Turbulence Model (IEC, 2009) to realize 3-component wind speed vectors encompassing the entire rotor plane. FAST makes use of the blade element momentum theory (Moriarty and Hansen, 2005) to generate time-series of aerodynamic load components at the hub of the OWT.

3.2. Hydrodynamic loads

Wave loading on slender structures like piles are calculated using the Morison equation (Chakrabarti, 2005). Here, the total load is obtained as the summation of drag and inertia components, arising from the velocity and acceleration of water particles, respectively. Morison equation gives the hydrodynamic force (*f*) per unit length of the vertical pile as:

$$f = \rho C_M \frac{\pi D^2}{4} \dot{u} + \frac{1}{2} \rho C_D |u| u \qquad (2)$$

where *D* is the diameter of the pile, *u* is the horizontal water particle velocity, $\dot{u}$ is the water particle acceleration, ρ is the density of water and C_M, C_D are hydrodynamic coefficients of inertia and drag, respectively. The dot represents acceleration. Long-crested irregular waves for dynamic analyses are modelled using the constant area discretization of the Joint North Sea Wave Project (JONSWAP) spectrum. The JONSWAP spectrum is valid for fetch-limited seas and homogenous wind conditions.

4. Results and Discussion

The generation of time series for stochastic wind and wave loading involves the use of pseudo-random number generators for realizing the random phases (Zwick and Muskulus, 2014). The use of different random seeds for the

same wind (or wave) data results in different time-series and hence, statistical uncertainty. This has to be taken care of by multiple simulations, involving different seed numbers. The results present herein are mean values from an ensemble size of 50, involving different seed numbers for generating wind and wave time series.

4.1. Effect of soil variability on natural frequency of OWT

As stated in Bhattacharya *et al.* (2013), a 3-bladed OWT is excited at the following: (a) the rotor frequency (1P), (b) the blade pass frequency (3P), (c) the wave loads and (d) the gusty winds. Economic considerations dictate that the frequency of the OWT lies in between the 1P and the 3P regions. This is termed as the soft-stiff design, which corresponds to a frequency band of 0.20 Hz to 0.35 Hz for the NREL 5MW-OWT. It is observed, from Table 2, that softening soils tends to increase the period of vibration and hence, result in a reduction in natural frequency. In the case of soft-clay, the natural frequency was found to dip into the unsafe 1P region, where the OWT structure becomes vulnerable to resonance. Pile penetration depth of 42 m and diameter of 6 m is considered for analysis.

Table 2. Variation of natural frequency

Soil type	Natural frequency (Hz)
Soft clay	0.16
Medium stiff clay	0.21
Stiff clay	0.24

4.2. Effect of soil variability on lateral response of OWT

For the considered pile penetration depth of 42 m, medium stiff and stiff clayey soil profiles show a variation of 60% in the lateral displacement at the mudline and 15% at the tower-top, respectively, as shown in Figure 2. The displacement of the OWT in soft clay is exceeds the serviceability limit of 0.2 m at mudline.
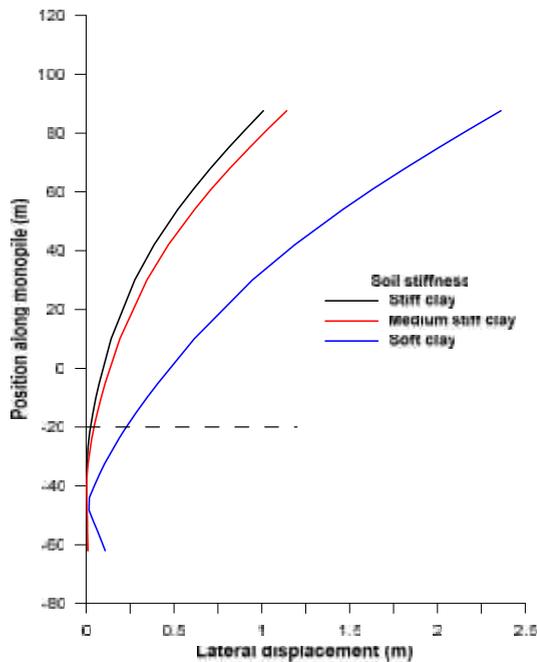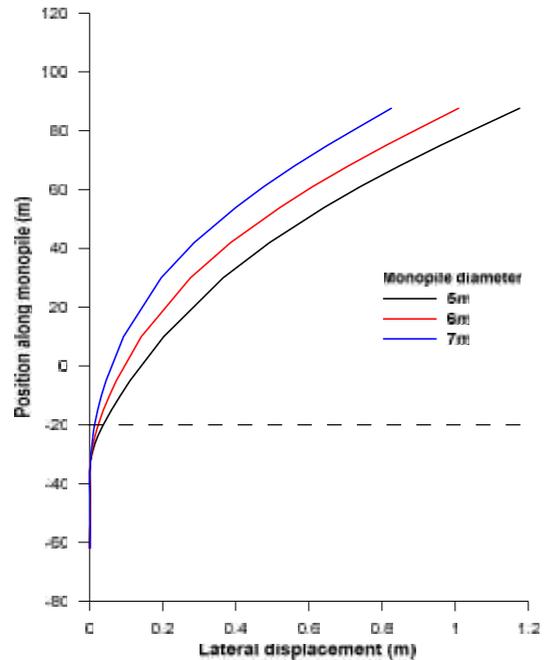
Fig. 2. Effect of soil variability

Fig. 3. Effect of pile diameter variation

4.3. Effect of pile diameter on lateral response of OWT

Three different pile diameters were considered for a penetration depth of 42 m, in stiff clay - 7 m, 6 m and 5 m. The thickness of the piles is defined according to Equation 1. It is observed from Figure 3, that an increase in pile diameter brings about a reduction in the lateral response of the OWT. This is due to the fact that the stiffness obtained from a $p - y$ curve is proportional to the diameter of the pile.

4.4. Effect of pile depth on lateral response of OWT

Stiff clay exhibits the same displacement profile for pile penetration depths from 42 m to 30 m. Medium stiff clay shows an increase in displacement with reduction in pile penetration depth. These results are shown in Figures 4a and 4b. A marked difference in the displacement of the embedded portion of the pile is also observed. For smaller penetration depths, the response of the OWT in soft clay escalates and this results in failure of the system.
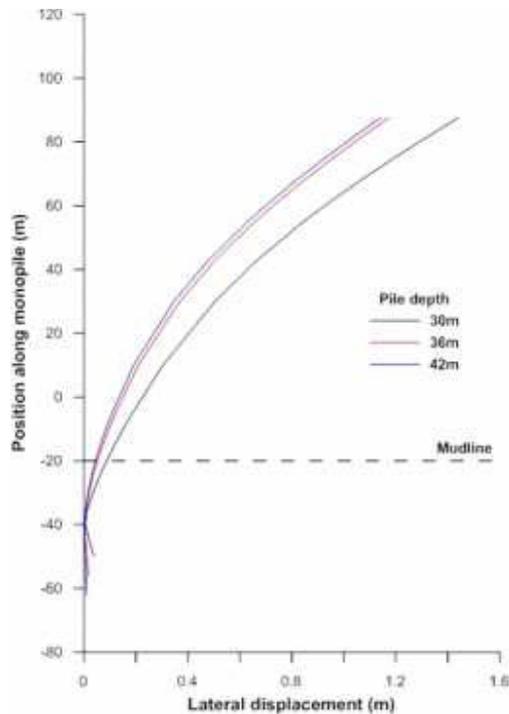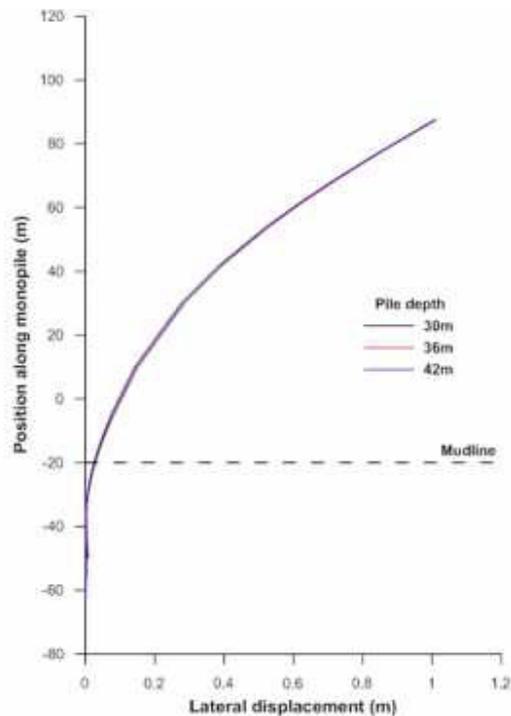
Fig. 4a. Medium stiff clay   Fig. 4b. Stiff clay

5. Conclusions

Decoupled aero-hydrodynamic simulations on a monopile in clay of varying stiffness underscore the importance of considering SSI in OWT studies. Softer soils increased the time-period of vibration and hence the natural frequency of the OWT shifted to the resonant region. Soil stiffness is the determining factor in the performance of OWTs in clayey soils. Soft clays were found to produce excessive motions that transcend the serviceability limit state, leading to failure. Stiff clays, on the other hand, produced relatively constant response with varying pile depth and diameter. Similar analysis is required to be extended for sandy soils as well as mixed soils, which would form a part of the future work.

Acknowledgements

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