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Probabilistic analysis of monopile-supported offshore wind turbine in clay

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ABSTRACT

The dynamic behaviour of monopile supported offshore wind turbines (OWTs) is considerably influenced by inherent variabilities of soil properties and loading. This study investigates the effect of uncertainties in soil shear strength properties, and wind and wave loads on the reliability of OWT structures founded in clay. The OWT system is modeled as an Euler-Bernoulli beam and soil-structure interaction is incorporated using the American Petroleum Institute based cyclic p-y relationships. The uncertainties in soil undrained shear strength, in the parameters and equations of the *p-y* method, and in wind velocity are considered. Random wave loads are estimated from the code specified power spectral density function of the vertical sea surface elevation. Uncertainties in OWT responses are quantified using Monte Carlo simulations. The effects of length and diameter of the monopile, vertical sea surface displacement spectrum, and the probability distribution of wind speed on the dynamic responses of OWT are investigated. The study shows that the various power spectral density functions of wave surface displacement and various probability density functions of wind speed have a marginal effect on the response and fatigue life of OWTs. The mean fundamental frequency of the OWT system is significantly affected by the variability of the undrained shear strength of clayey soil.

1. Introduction

Design of foundations plays an important role in the overall design of offshore wind turbines (OWTs) because the foundation accounts for about 30–40% of the total project cost [4–7]. Monopiles are economical foundation options for OWTs installed at shallow water depths [1–5], and are subjected to complex aerodynamic and hydrodynamic forces arising from wind and ocean waves [16,17]. The tolerance in terms of maximum allowable rotations of the monopile head in a vertical plane at seabed (i.e. serviceability limit state (SLS) criterion) is considered as design basis of OWT [18]. Likewise, fatigue limit state (FLS) of minimum 10^7– 10^8 load cycles over 20–25 years to be sustained under long term wind and wave loads [18–22]. In addition to SLS and FLS criteria, the other design criterion is that the fundamental frequency of OWT should not interfere with the rotor frequency (1P), tower shadowing frequency (3P for 3 bladed OWT), and wave frequency [8–15,19,21,22,27,28,78].

Estimation of OWT response against applied loads and its fundamental frequency are associated with significant uncertainties because of inherent soil variability, uncertainty in applied loads, and uncertainty in the analysis models [23–25]. Uncertainty in soil properties arises from the heterogeneity of seabed and limited number of sampling [25,34]. Several studies in the past focused on probabilistic aspects of OWT design [24,32–43]. Out of the probabilistic studies performed on OWT, most focused on reliability based design optimization of OWT considering uncertainties in loading and material properties of structure [32–35,37–43], and the uncertainty in soil properties were not considered. A few of these studies focused on the response of OWT considering uncertainties in loading and soil shear strength parameters [24,36];`however, the dynamic soil-monopile-structure interaction was not considered. In all these studies, significant variation in the responses of OWT was observed because of the incorporation of variability in loading and soil parameters. Various design codes related to OWT design, such as Det Norske Veritas (DNV) [18,26], Germanischer Lloyd (GL) [29], International Electrochemical Commission (IEC) [30] and American Bureau of Shipping (ABS) [31], advocate the use of probabilistic design models to calibrate partial factors used in design and special design requirements [24]; however, no explicit methodology on reliability based OWT design incorporating the effects of dynamic soil-structure interaction is yet available in these codes. In order to get further insights into the effect of different uncertainties on OWT performance, a comprehensive assessment of the dynamic behaviour of OWT considering the variability of wind and wave loading and soil parameters is required [16,44].

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In this paper, the effects of uncertainties in soil properties and applied loads on the response of monopile-supported OWTs are investigated using a nonlinear soil-structure interaction analysis performed within a probabilistic framework. Dynamic finite element (FE) analysis is performed to obtain the OWT responses in the time domain. The monopiles are assumed to be embedded in clayey soil, and are analyzed using the beam-on-nonlinear-foundation approach. The American Petroleum Institute (API) [45] recommended cyclic *p-y* curves for soft clays are used to model the lateral soil resistance. This study primarily examines the lateral behaviour of OWT; therefore, the monopile is assumed to rest on a firm ground so that the vertical pile displacement is considered negligible compared with the corresponding horizontal pile displacement. The uncertainties in the soil-structure interaction model, soil properties, wave load, and wind load are considered, and combined through Monte-Carlo (M-C) simulations to obtain the probability distributions of the maximum mudline rotation, maximum rotation at tower top, and fatigue life. The statistics of OWT responses are examined as functions of embedded length and diameter of monopiles, soil stiffness, wind velocity, spectral density of waves, and probability density function of wind speed. The probabilities of failure based on SLS criterion for OWT design are also obtained.

2. Deterministic model

2.1. Problem definition

An OWT supported by a monopile embedded in a clay layer is considered in this study (Fig. 1). The tower is assumed to behave like an Euler-Bernoulli beam with flexural rigidity E_pI_p,. The monopile also behaves like an elastic beam following Euler-Bernoulli theory, with flexural rigidity E_pI_p, and resists lateral loads. Uniform cross-sections for the monopile and the tower are assumed for simplicity. The monopile is assumed to rest in a bed of nonlinear Winkler springs representing the resistance of the clay layer against lateral pile movement. The horizontal Winkler soil springs are assumed to be attached with each beam element of the monopile and generate the lateral resistance against monopile movement following the *p-y* model recommended by API [45]. The tower and monopile are discretized into beam elements with three degrees of freedom (lateral and vertical displacements, and rotation) at each node.

The wind thrust acting on the rotating blades eventually gets transmitted to the tower at the hub in the form of the force F_b. F_b is considered dynamic with a frequency equal to the rotor frequency, and is designated as 1P load (i.e., once per revolution). Two additional forces $F_{1\text{tower}}$ and $F_{2\text{tower}}$ act on the tower — one over the part of tower obstructed during the movement of the blades ($F_{1\text{tower}}$) and the other on the tower unobstructed by the blades ($F_{2\text{tower}}$). The obstruction from blade rotation occurs three times per revolution which makes $F_{1\text{tower}}$ a dynamic force on the tower with a frequency three times of 1P (designated as 3P load). The load $F_{2\text{tower}}$ on tower is static. The shaded region in wind velocity profile (Fig. 1) shows the region need to be considered for the estimation of F_b, $F_{1\text{tower}}$ and $F_{2\text{tower}}$. The forces $F_{1\text{tower}}$ and $F_{2\text{tower}}$ act at the centroid of the shaded area representing wind velocity profile. The wave force F_w is assumed to be dynamic and acts at the mean sea level (MSL) with a wave frequency.

2.2. Numerical model

Finite element analysis is carried out using OpenSees [52] to estimate the responses of the OWT system. Two-noded beam elements (in which the beam deflection and slope are the nodal degrees of freedom, which are interpolated using the cubic Hermitian shape functions) are used to model the monopile and tower. A roller support is introduced at the base of monopile to prevent vertical displacement. The rotor blades, nacelle and hub are combined into a single mass M_{RNA} placed at the top node of the tower with rotary inertia J_{RNA} (c.f. Fig. 1). The soil resistance against lateral pile movement is modeled as nonlinear springs that follow the API *p-y* curves. The overall damping is modeled as a series of viscous dashpots connected to the monopole such that each dashpot is placed in parallel with each soil spring. A convergence study was carried out and it was observed that 1 m length of beam elements with soil springs attached at 1 m interval produced satisfactory results. The dynamic equation of motion of the system is solved by using Newmark's average acceleration method (the 'transient analysis' solver in OpenSees [52] was used). The nonlinearity in *p-y* curves is accounted for by using a simple step-load controlled incremental algorithm

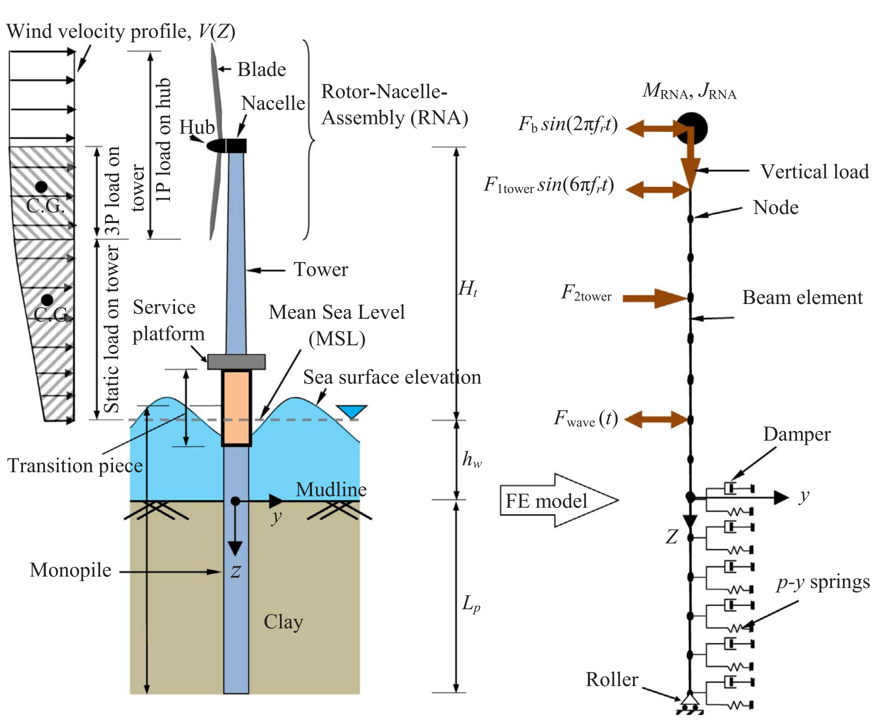

Fig. 1. Schematic diagram of OWT system in clay and the corresponding finite element model.