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Effect of monopile foundation modeling on the structural response of a 5-MW offshore wind turbine tower

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ABSTRACT

Offshore wind turbine towers experience large base moments because of wind and wave loading. The flexibility of the foundation should be considered when analyzing the structural response of towers. Previous studies showed that conventional *p*–*y* curves are not suitable in designing the foundation. More advanced methods, such as the finite element method, are necessary to model the offshore wind turbine foundation. In addition, these studies focused on the analysis of the foundation itself, so the effect on the structural response of the tower merits further research. The present study aimed to compare different foundation modeling approaches, focusing on their effects on the structural response of the wind turbine tower. We integrated wind turbine aerodynamic simulation with different models of the foundation. We confirmed that ignoring the flexibility of the foundation caused significant error in wind turbine tower behavior. Between the *p*–*y* curve-based model and finite element-based model, the change in maximum moment was insignificant, but the maximum tilt angle increased over 14% in the finite element model. Therefore, the finite element approach is recommended to obtain a conservative design when large tilt angles may cause serviceability issues.

1. Introduction

Offshore wind turbine structures are distinguished from other offshore structures, such as oil and gas platforms. The tower is slender with large lateral forces at the top, thereby experiencing large moments at the tower base. Consequently, they pose new challenges in the analysis, design, and construction of the foundation. The foundation should not only support vertical loading but also prevent failure caused by the large moment. Foundation types for offshore wind turbines include monopiles, gravity bases, space-frames, and floating structures. The monopile foundation is the most commonly used type for shallow waters (less than 30 m in depth), which is the focus of this paper.

One of the earliest studies on the foundation modeling of offshore wind turbines was by Zaaijer (2002). The author compared the distributed spring model, cantilever with the effective fixity length, stiffness matrix-based approach, and uncoupled spring model. The stiffness matrix at the mudline was found to be a good approximation for modeling foundation flexibility. Van der Tempel (2006) discussed a similar approach for foundation modeling. Recent studies investigated the foundation effect more thoroughly while considering wind turbine aerodynamics (Jonkman et al., 2007; Bush and Manuel, 2009); however, these studies relied on conventional *p*–*y* curve approach in modeling the effect of soil. The *p*–*y* curve approach is commonly used for other offshore structures, such as oil platforms (API, 2007). A recent report highlighted the limitation of using conventional models for offshore wind turbine foundations (TRB, 2011). This report stated that “monopile substructures for wind turbines exceed the diameters and experience base of the oil and gas industry” and “extrapolating current practice to the larger sizes can introduce unintended effects” (TRB, 2011, p. 57). Previous studies also pointed out that conventional *p*–*y* curves may not be suitable for the design of offshore wind turbine foundation, and the finite element method (FEM) has been used as a more accurate alternative. These studies include the works by Lesny and Wiemann (2006), Lesny et al. (2007), Sørensen et al. (2009), Hearn (2009), Hearn and Edgers (2010), and Achmus and Abdel-Rahman (2012).

The present study aimed to compare *p*–*y* curve-based foundation modeling and FEM-based foundation modeling, while considering wind turbine aerodynamics. Although new studies on FEM-based modeling exist, our understanding of the effect of foundation modeling on wind turbine tower behavior is quite limited. By integrating wind turbine aerodynamic simulation and

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FEM-based foundation modeling, we aimed to quantify the effect on the response of the wind turbine tower. Structural responses of the tower will be compared while changing foundation modeling. Fixed boundary, p–y curve-based spring model, and FEM-based model were also compared in this paper.

2. Description of the wind turbine and foundation

We used the 5 MW reference wind turbine from the National Renewable Energy Laboratory (NREL) in the analysis (Jonkman et al., 2009). The NREL developed the reference turbine to aid concept studies and research activities on offshore wind energy. Fig. 1 shows a schematic of the reference wind turbine. It has three blades with variable speed and pitch control. The cut-in, rated, and cut-out wind speeds are 3, 11.4, and 25 m/s, respectively. The rotor diameter is 126 m. The tower height is 87.6 m, and the water depth is 20 m. The masses of the rotor, nacelle, and tower are 110, 240, and 347.5 t, respectively. The tower has a base diameter of 6 m (wall thickness = 0.027 m) and top diameter of 3.87 m (wall thickness = 0.019 m). Further details on the wind turbine can be found in Jonkman et al. (2009).

The support structures used for offshore wind turbines include monopiles, gravity bases, space-frames, and floating structures. This study investigated the monopile foundation, which is the most commonly used type for shallow waters (less than 30 m in depth). The monopiles can be installed into sandy and clayey soils by driving or vibrating. These soils can be found widely at different offshore sites, such as the North Sea or Baltic Sea in Europe for sandy soil, and the Gulf of Mexico or Western Australia for clayey soils. In this study, two representative soil profiles were assumed, which were adapted from the works of Passon (2006) (for sandy soil) and Chen et al. (2009) (for clayey/sandy soil), as shown in Fig. 2. The sandy soil profile was named "stiff soil", whereas the clayey and sandy soil profile was named "soft soil". In the figure, the parameters γ', $E'(E_u)$, $\nu'(\nu_u)$, ϕ', Ψ', c' and s_u present the effective unit weight, Young's modulus, Poisson's ratio, effective friction angle, dilation angle, cohesion and undrained shear strength of soils, respectively. For p–y curve analyses, the soil modulus k in sand was selected based on the ϕ' values following recommendations of the API sand models (API, 2007; Isenhower and Wang, 2012), and the soil strain parameter ε_{50} in clay was determined based on the undrained shear strength of clay (Matlock, 1970; Isenhower and Wang, 2012).

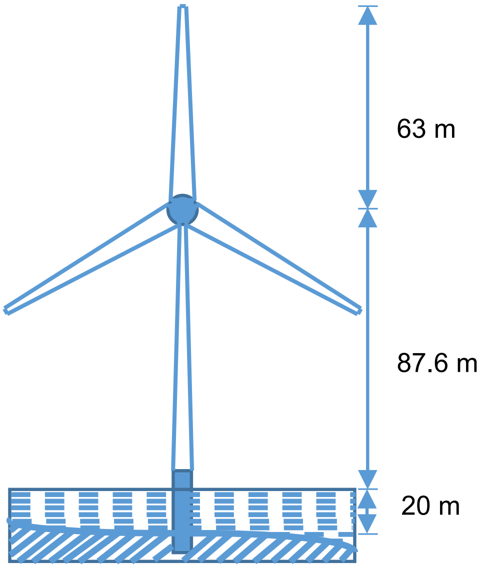

Fig. 1. Schematic of the NREL 5-MW offshore wind turbine.

The steel pile with a diameter of 6 m was assumed to be driven up to 36 and 40 m into the stiff soil and soft soil, respectively. The wall thickness of the piles was set to 6 cm. The piles had a Young's modulus (E_s) of 210,000 MPa with a yield stress (σ_y) of 205 MPa.

3. Modeling of the foundation behavior

3.1. Coupled spring model

The monopile and soil influence the structural response of the wind turbine. To model the effect of the foundation, we employed the coupled spring model shown in Fig. 3 (Bush and Manuel, 2009). Other researchers have shown that this approach accurately models the effects of soil in wind turbine simulation (Jonkman et al, 2007).

The first step in the coupled spring approach is to define the flexibility matrix as follows:

$$\begin{Bmatrix} u_h \\ u_r \end{Bmatrix} = \begin{bmatrix} S_{hh} & S_{hr} \\ S_{rh} & S_{rr} \end{bmatrix} \begin{Bmatrix} F_h \\ F_r \end{Bmatrix} \tag{1}$$

in which the two-by-two matrix is the flexibility matrix, u_h is the lateral displacement, u_r is the rotation, F_h is the lateral force, and F_r is the moment. The displacement and force are from the top of the pile (the mudline). The first column of the flexibility matrix (S_{hh},S_{rh}) can be obtained by applying the lateral force only (while $F_r = 0$) and recording the displacement and rotation. Similarly, the second column of the flexibility matrix can be obtained by applying the moment only and recording the displacement and the rotation. Once the flexibility matrix is obtained, the following stiffness matrix can be determined by inverting it:

$$\begin{Bmatrix} F_h \\ F_r \end{Bmatrix} = \begin{bmatrix} K_{hh} & K_{hr} \\ K_{rh} & K_{rr} \end{bmatrix} \begin{Bmatrix} u_h \\ u_r \end{Bmatrix} \tag{2}$$

in which the two-by-two matrix is the stiffness matrix. To use the coupled spring model, we need to obtain force-displacement curves, which will be explained in the next section.

3.2. Soil models and validation of finite element modeling

Three different soil modeling approaches, namely, the fixed boundary model, p–y curve-based spring model, and FEM-based spring model were compared in this study. The fixed boundary model ignores the flexibility of the soil. The bottom of the wind turbine is modeled as completely fixed. This approach is inaccurate, it will be analyzed and compared with other approaches.

The p–y curve is a commonly used method to analyze the horizontal load–displacement behavior of piles. The springs in the p–y-curve method represent soil behavior. Theoretically, the p–y curve method is based on the theory of subgrade reaction, representing the soil horizontal resistance per unit length (p) of a pile when the pile is translated laterally by a displacement (y) into the soil. The p–y method was implemented through the LPILE V6.31 program (Isenhower and Wang, 2012) with the API sand model (O'Neill and Murchison, 1983) and soft clay model (Matlock, 1970). The Clay 3 layer in Fig. 2b is considered as a stiff clay layer, so this layer was simulated by the stiff clay model (Reese et al., 1975).

For the FEM-based spring model, the foundation was modeled using 3D solid elements. Fig. 4 shows a typical finite element (FE) mesh used in the analysis. Load–displacement curves were obtained from the FEM simulations, which were then converted to equivalent coupled springs. Small-strain FE analysis was conducted