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THE INFLUENCE OF FOUNDATION MODELING ASSUMPTIONS ON LONG-TERM LOAD PREDICTION FOR OFFSHORE WIND TURBINES

Erica Bush
University of Texas at Austin
Austin, TX, USA

Puneet Agarwal
University of Texas at Austin
Austin, TX, USA

Lance Manuel
University of Texas at Austin
Austin, TX, USA

ABSTRACT

In evaluating ultimate limit states for design, time-domain aeroelastic response simulations are typically carried out to establish extreme loads on offshore wind turbines. Accurate load prediction depends on proper modeling of the wind turbulence and the wave stochastic processes as well as of the turbine, the support structure, and the foundation. One method for modeling the support structure is to rigidly connect it to the seabed; such a foundation model is appropriate only when the sea floor is firm (as is the case for rock). To obtain realistic turbine response dynamics for softer soils, it is important that a flexible foundation is modeled. While a single discrete spring for coupled lateral/rotational motion or several distributed springs along the length of the monopile may be employed, a tractable alternative is to employ a fictitious fixed-based pile modeled as an “equivalent” cantilever beam, where the length of this fictitious pile is determined using conventional pile lateral load analysis in combination with knowledge of the soil profile.

The objective of this study is to investigate the influence of modeling flexible pile foundations on offshore wind turbine loads such as the fore-aft tower bending moment at the mudline. We employ a utility-scale 5MW offshore wind turbine model with a 90-meter hub height in simulations; the turbine is assumed to be sited in 20 meters of water. For a critical wind-wave combination known to control long-term design loads, we study time histories, power spectra, response statistics, and probability distributions of extreme loads for fixed-base and flexible foundation models with the intention of assessing the importance of foundation model selection. Load distributions are found to be sensitive to foundation modeling assumptions. Extrapolation to rare return periods may be expected to lead to differences in derived nominal loads needed in ultimate limit state design; this justifies the use of flexible foundation models in simulation studies.

INTRODUCTION

Nominal loads for the design of wind turbines in ultimate limit states are generally established from time-domain aeroelastic response simulations. The accuracy of these derived loads depends on the number of simulations and on how realistically the models used to represent the turbine, support structure, and foundation describe the true structural response. One potential shortcoming in modeling foundations relates to their flexibility. A single pile (often referred to as a monopile) is the most common type of foundation used today for offshore wind turbines; the support structure connects to such a pile foundation that extends some depth below the mudline. One way a monopile foundation could be modeled is by means of a rigid connection at the mudline. This model ignores the soil profile and the associated soil-pile stiffness and, as such, would not account for the pile’s expected lateral/rocking movement. Such simplifying assumptions could only adequately simulate the behavior of a monopile founded in rock. Many offshore wind turbines, however, are founded on softer soils where the monopile experiences at least some movement at and below the mudline. It is therefore worth assessing the accuracy of the use of a fixed-base model versus a flexible foundation model. In the present study, we carry out fixed-based model simulations and study turbine loads (specifically, the fore-aft tower bending moment). These are compared with loads derived using a flexible foundation model. This latter model utilizes stiffness properties derived from the soil profile at the location of the turbine by means of a conventional pile foundation analysis and appropriate *p-y* lateral load-deflection relationships. The flexible foundation model involves derivation of an “apparent fixity length” representing a distance below the mudline where an equivalent cantilever yields the same lateral movement and rotation as the monopile experiences in the pile analysis with the true soil properties. The mass per unit length of the equivalent cantilever is adjusted to match the sub-soil mass of the original pile in order to realistically account for inertia effects in the flexible foundation model used.

We derive load distributions using time-domain aeroelastic simulations for fixed-based and flexible foundation models. The simulations are carried out for critical environmental conditions that have been shown to control long-term tower loads [1]. By comparing distributions for extreme tower loads, we seek to gain insight into the importance of foundation modeling assumptions on long-term design loads for offshore wind turbines.

WIND TURBINE MODEL

A 5MW wind turbine model developed at the National Renewable Energy Laboratory (NREL) [2] closely representing utility-scale offshore wind turbines being manufactured today is used here. The turbine is a variable-speed, collective pitch-controlled machine with a maximum rotor speed of 12.1 rpm; its rated wind speed is 11.5 m/s. It has a hub 90 meters above the mean sea level and a rotor diameter of 126 meters. It is sited in 20 meters of water. The support structure and the wind turbine's tower are modeled as a single continuous cylinder with varying diameter and wall thickness. The monopile support structure for the wind turbine tower has an outer diameter of 6 m and a wall thickness of 6 cm. For the fixed-base case, the support structure starts rigidly attached to the mudline and extends to 10 m above the mean sea level; for the flexible foundation case, the support structure starts rigidly attached at a depth of the apparent fixity length (defined later) below the mudline and extends to 10 m above the mean sea level. The turbine tower attached to the support structure tapers linearly upward. At 10 m above the mean sea level, the tower has an outer diameter of 6 m and a wall thickness of 2.7 cm; at the top, the tower has an outer diameter of 3.87 m and a wall thickness of 1.9 cm. The density of steel of which the tower is constructed is taken to be 8,500 kg/m^3, and the modulus of elasticity is taken to be 2.1×10^5 MN/m^2. In previous studies [1], we have assumed a rigid connection at the mudline for this turbine. In the present study, for the purposes of carrying out analyses using a flexible foundation, a penetration depth of 36 m is assumed for the monopile. Additional details on the flexible foundation are presented later.

A Kaimal power spectrum and an exponential coherence spectrum are employed to describe the inflow turbulence random field over the rotor plane, which is simulated using the computer program, TurbSim [3]. For hydrodynamic loading on the support structure, irregular long-crested waves are simulated using a JONSWAP spectrum [4]. The hydrodynamic loads are computed using Morison's equation [5] and take into account stretching corrections for wave kinematics.

After obtaining time histories of the wind inflow turbulence field from TurbSim, the computer program, FAST [6], is used to carry out stochastic time-domain simulations of the turbine response. FAST accounts for aerodynamic loads based on the inflow turbulence input; it also account for hydrodynamic loads by first simulating a random sea surface elevation process, and then applying appropriate wave kinematics and inertia and drag force computation using Morison's equation. For the structural response computation, FAST employs a combined modal and multi-body dynamics formulation.

TURBINE RESPONSE SIMULATIONS

In order to investigate the influence of foundation modeling assumptions on extreme wind turbine tower loads, simulations are carried out for a single wind speed and wave height pair. The hub-height ten-minute average wind speed, V, of 16 m/s and the significant wave height, H_s, of 5.5 m represent a joint wind-wave environmental state or condition that was shown to be critical for extreme tower loads for a fixed-based wind turbine at the 20-year return period level based on an Inverse First-Order Reliability Method (Inverse FORM) [1]. Here, we are interested in a comparison of tower load statistics based on simulations when either a fixed-based or a flexible foundation model is employed. For each foundation model considered, a total of 150 ten-minute turbine response simulations are carried out. A description of the flexible foundation model development is presented next. This is based largely on a previous study by Passon [7] that is also summarized by Jonkman et. al [8].

FLEXIBLE FOUNDATION MODEL

The flexible foundation model used in this study is based on the apparent fixity length model where the true monopile and surrounding soil medium is replaced by a cylinder that is fixed not at the original mudline but at a lower level that is derived as a point of apparent fixity for the cantilevered cylinder [7, 8]. In the flexible foundation model, not only is the fixity length derived but properties of the pile below the mudline can be different from those above and these are derived as well. Figure 1 provides schematics of the fixed-base and flexible foundation models.

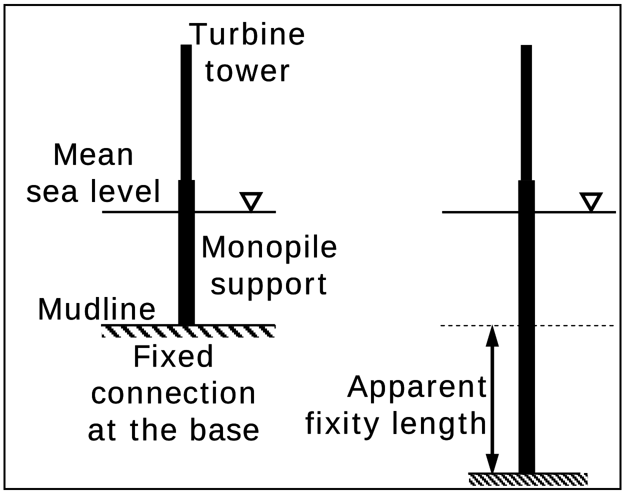


Figure 1: Schematic representations of the two models used for the foundation showing the fixed-base foundation model (figure on left) and the flexible foundation model (figure on right) where an apparent fixity length is employed.

The apparent fixity length (l) represents the depth below the mudline where the cantilevered monopile is to be modeled so as to have the stiffness of the true pile-soil system. Given specified levels of shear (F) and moment (M) at the true mudline, lateral deflections and rotations at the mudline are first determined using the known soil profile, penetration depth, and pile dimensions/properties. This is typically carried out using a pile lateral load analysis program such as LPILE [9]. Note that the axial force in the pile is also needed in order to account for secondary moments (so-called P-Δ effects) when the pile deflects laterally. However, the shear and moment are of greater importance since deformations are generally small leading to negligible secondary effects as was verified in this study.

Since the nonlinear p-y curves yield different foundation stiffness values (and, thus, different apparent fixity lengths) depending on the applied shear and moment at mudline, the selected F and M values are important. In our analyses, we employ typical mudline shear and moment values based on fixed-base analyses. Still, even with 150 simulations for fixed-based foundations, a range of mudline shear and moment values is experienced. We examine flexible foundation models covering this range of experienced forces. The soil profile at the site under consideration is shown in Fig. 2; this is the same profile used by Passon [7]. In the figure, γ refers to the effective weight, ϕ' refers to the angle of internal friction, and k refers to the initial modulus of the subgrade reaction. These properties describe the sands in the three different layers; the p-y curves for the lateral force-displacement relationships of the pile are based on guidelines from the American Petroleum Institute [10].

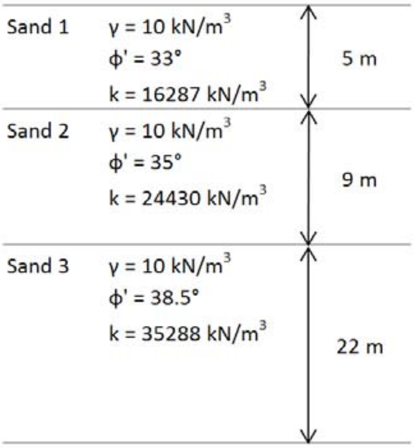


Figure 2: Soil profile used in the numerical studies.

The rotation and lateral deflection at the mudline are calculated using LPILE. The true monopile foundation is then replaced by a cantilever that is fixed at some depth below the mudline. The length of this cantilever is that which will produce the same rotation and deflection at its free end (the original mudline) under the applied loads as is found from the pile analysis using LPILE. This is referred to as the apparent fixity length (l) and is derived along with the flexural rigidity (EI) of the cantilever using the following equations:

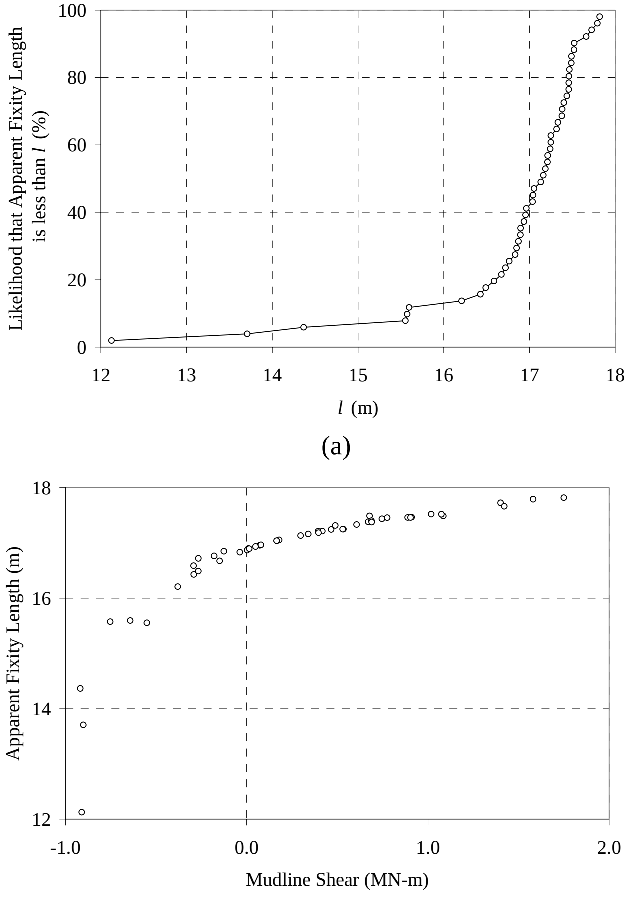
$$\begin{aligned} w &= \frac{Fl^3}{3EI} + \frac{Ml^2}{2EI} \\ \theta &= \frac{Fl^2}{2EI} + \frac{Ml}{EI} \end{aligned} \tag{1}$$

where w is the deflection and θ is the rotation at the mudline. To model this new fictitious pile in FAST, its length, flexural rigidity, and mass distribution are required. The length and flexural rigidity are determined as described by Eq. (1). The mass distribution is kept the same as the mass per unit length of the monopile above the mudline. The mass of the equivalent cantilever also closely matches the sub-soil mass of the original pile and, thus, realistically accounts for inertia effects in the flexible foundation model.

To arrive at values of F and M for the pile analysis and for computation of the apparent fixity length, l, 150 ten-minute simulations were run for the fixed-base case. Time histories as well as summary statistics for F and M were obtained; ensemble averages over the 150 simulations of the mean (μ), standard deviation (σ), and maximum (max) values of the shear, moment, and axial force at the mudline were computed. Table 1 summarizes derived apparent fixity lengths and flexural rigidity values for flexible foundation models that were developed using three different fixed-base mudline force combinations: (a) using mean (μ) values; (b) using "mean plus one standard deviation" values ($\mu + \sigma$); and (c) using maximum values (max). The deflections and rotations at the pile head shown in Table 1 were based on LPILE analyses. As can be seen from Table 1, the apparent fixity lengths and flexural rigidities for the cantilever that serves as a representation of the flexible foundation are only slightly different for the three mudline force cases. This suggests that the soil behavior is almost linear for the pile and soil properties (i.e., the profile) studied here and for the range of forces encountered in simulations with the selected wave height and wind speed. The apparent fixity length varies between 17 and 18 meters. Indeed, if the shear, moment, and axial force values are allowed to take on a wide range of values that were obtained in the fixed-base simulations, with representative contemporaneous values of the forces taken randomly at different times during each ten-minute simulation, the apparent fixity lengths remained in a narrow range. This can be confirmed by studying Fig. 3 which summarizes computations of the apparent fixity length, l, for 50 randomly drawn contemporaneous shear, moment, and axial forces from simulations with H_s = 5.5m and V = 16 m/s. Clearly, greater than 60% of the time, the apparent fixity length is between 17 and 18 meters. Also, in the range of most likely shear force values, the apparent fixity length is close to 17 meters; only for small shear values does this apparent fixity length reduce by more than a meter. We might note here that only for larger wave heights and/or larger wind speeds, shear forces might be expected to be larger and, thus, result in greater apparent fixity lengths in flexible foundation models.

Table 1: Summary of the derived flexible-foundation models based on mudline forces at three different levels—mean (μ), mean + 1 standard deviation ($\mu + \sigma$), and maximum (max). The mudline forces used in the three cases are M (moment) and F (shear); the mudline lateral displacement (w) and rotation (θ) at the top of the file are computed using LPILE. The derived apparent fixity length (AFL) and flexural rigidity of the pile (EI) are also shown.

Case	Force basis	M	F	W	θ	AFL	EI
		(MN-m)	(MN)	(m)	(rad)	(m)	(MN-m^2)
1	μ	45.15	0.40	0.0065	-0.0007	17.20	1,125,200
2	$\mu + \sigma$	57.08	1.02	0.0092	-0.0010	17.50	1,142,800
3	max	90.59	2.45	0.0167	-0.0017	17.94	1,155,400



(a)

(b)

Figure 3: Study of apparent fixity lengths in flexible foundation model based on random samples of contemporaneous shear force, bending moment, and axial force at the mudline for $V = 16$ m/s and $H_s = 5.5$ m) – (a) likelihood of different derived apparent fixity lengths; (b) variation of apparent fixity length with mudline shear force.

Figure 4 shows power spectral density functions of the fore-aft tower bending moment for the fixed-based model and for the three alternate flexible foundation models presented in Table 1. As can be seen, for these three models, the tower loads are generally comparable and each is quite different from the loads resulting from a fixed-base analysis. In the following, we focus only on Case 2 for detailed analyses of the flexible foundation response studies. This case corresponds to "mean plus one standard deviation" ($\mu + \sigma$) mudline forces from a fixed-base analysis that are used to tune the foundation flexibility.

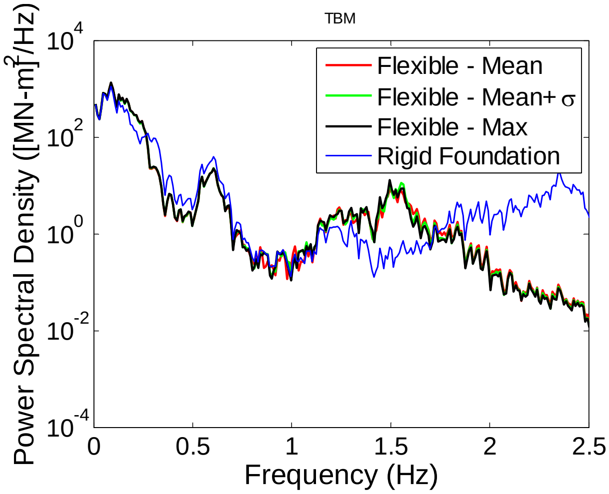


Figure 4: Power spectral density functions of the fore-aft tower bending moment for $V = 16$ m/s and $H_s = 5.5$ m with different foundation models—the fixed-base case and three alternative flexible foundation cases corresponding to different derived apparent fixity lengths and stiffnesses for the soil.

NUMERICAL STUDIES

A total of 150 ten-minute simulations were run for the fixed-based model and for the flexible foundation model for the selected environmental condition corresponding to a hub-height ten-minute average wind speed, V, of 16 m/s and a significant wave height, H_s, of 5.5 m. Our interest is primarily in the fore-aft tower bending moment at the mudline. Figure 5 shows representative 200-second segments from a single ten-minute simulation; longitudinal wind speed, sea surface elevation, and the fore-aft tower bending moment for the fixed-base and flexible foundation models are shown. The wave input has an influence on the tower loads as is evident from the figure. Upon comparing fixed-base and flexible foundation tower loads, it can be seen that the energy at higher frequencies is diminished and the energy at some intermediate frequencies is enhanced with the flexible foundation model. This can be confirmed by also studying the power spectra in Fig. 4. The rigid fixed-base model clearly has greater high-frequency content; the flexible foundation model with the smaller soil-pile stiffness expectedly loses some of this high-frequency energy.

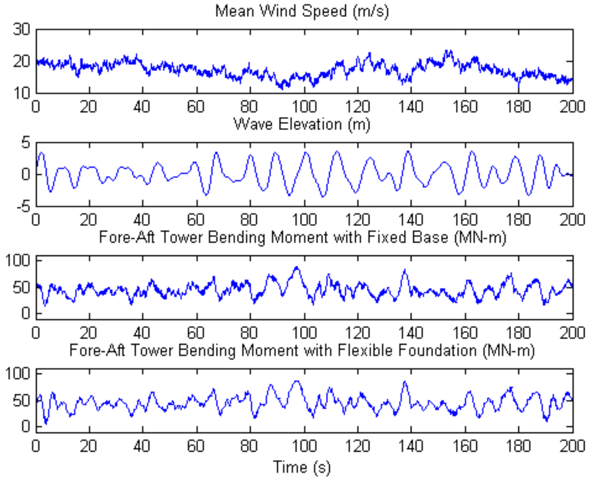


Figure 5: A representative 200-second segment of the hub-height longitudinal wind speed, the sea surface elevation, and the fore-aft tower bending moment for two cases (fixed-base and flexible foundation models) taken from a single 10-minute simulation for $V = 16$ m/s and $H_s = 5.5$ m. The flexible foundation model's derived stiffness is based on mudline forces derived using mean + 1 standard deviation forces from the fixed-base case.

Table 2 summarizes fore-aft tower bending moment statistics based on 150 ten-minute simulations for the fixed-base and the flexible foundation models. Gross second-order statistics (such as standard deviation) are higher for the flexible foundation by almost 10% while maxima are higher by about 2% compared to the fixed-base case. Note that these differences are for the soil profile studied. It is possible that greater deviations could result for softer soils or more severe seastates; hence, modeling of foundation flexibility does have some influence on tower loads. It is interesting to note that load extremes are not greatly different for the fixed-base and flexible foundation cases; this is because there is an offsetting effect of a lower peak factor (less skewed distribution) for the flexible foundation case despite the larger standard deviation in that case. Since the load maximum is obtained as the mean plus a peak factor times the standard deviation, the smaller peak factor in the flexible foundation case even though multiplied by a larger standard deviation leads to a larger maximum (than in the fixed-base case) but not by a great amount. We make two additional observations here. First, the mean value of the tower load is only slightly different for the fixed-base and flexible foundation models. Hence, the different stiffnesses of the two models alone (and their direct influence on the static response and the mean) cannot explain the difference in load maxima; only dynamic considerations (also evident in Figs. 4 and 5) can do so. A second point to note is that, when rotor loads such as in-plane and out-of-plane bending moments at a blade root are studied, differences resulting from alternative foundation models are even smaller than with tower loads. Ten-minute maxima were different by less than 1%. This is not surprising since it is expected that support structure and foundation modeling assumptions influence local response near the tower base to a greater extent than they do rotor loads.

Figure 6 shows estimates of probability distribution curves for the fore-aft tower bending moment as obtained with the fixed-base and the flexible foundation models. These distributions shown as probability of exceedance estimates for any specified tower bending moment value are based on 150 ten-minute simulations. Variability in the load maxima is evidently somewhat greater with the flexible foundation model, even if only slightly so. Presumably, when such probability distributions are used in statistical load extrapolation to derive nominal loads for design against ultimate limits for very much smaller probabilities of exceedance, small deviations due to foundation modeling assumptions seen in the simulated sample might lead to greater disparities in design load predictions.

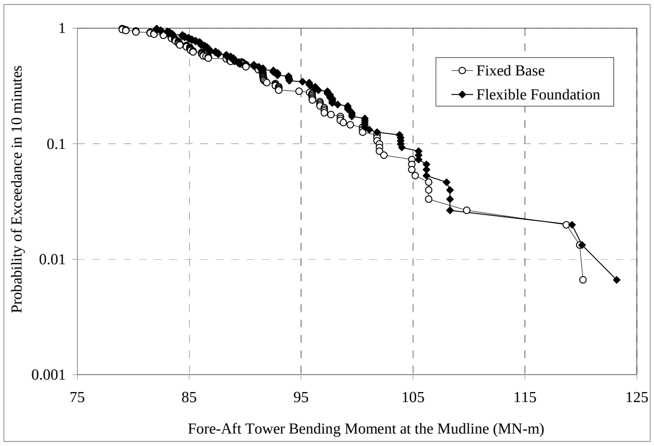


Figure 6: Probability of exceedance of different tower bending moment levels (for fixed-base and flexible foundation models) for $V = 16$ m/s and $H_s = 5.5$ m.

Table 2: Ensemble averages of various statistics of the fore-aft tower bending moment based on 150 ten-minute simulations. Peak factors (PF) are computed by subtracting mean values from maxima/minima and dividing by the standard deviation.

Foundation Model	Max (MN-m)	Min (MN-m)	Mean (MN-m)	Std. dev (MN-m)	Skewness	Kurtosis	PF(max)	PF(min)
Fixed-Base	90.6	6.4	45.2	11.9	0.22	3.25	3.81	-3.25
Flexible	92.3	3.2	45.5	13.0	0.09	3.08	3.60	-3.25

CONCLUSIONS

A flexible foundation model has been employed to study extreme tower loads for an offshore wind turbine. The study is motivated by the need to assess the degree of influence on loads of foundation modeling assumptions and to assess the accuracy of simpler fixed-base models for foundations that do not account for the soil-pile stiffness in typical monopile foundations. The flexible foundation model makes use of details related to the soil profile, *p-y* curves for lateral response of the soil-pile system, and the notion of an apparent fixity length or distance below the true mudline that is derived on the basis of the nonlinear *p-y* curves and realistic applied forces at the mudline.

Time-domain simulations were carried out and show that there is reduced high-frequency energy in turbine loads when foundation flexibility is taken into account. Load extremes are seen to be slightly larger for flexible foundations; the standard deviation (variability in the load process) is also somewhat larger and to a greater degree than for extremes. Probability distribution curves for tower bending moment estimated from simulations show greater variability for flexible foundations; extrapolation to rare return periods is expected to lead to even wider differences between fixed-base and flexible foundation model predictions.

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