Reliability analysis of monopile offshore wind turbine support structures

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ABSTRACT: We probe the reliability of monopile support structures designed to support industrial scale turbines along the coastal United States using stochastic models for the wind and wave loadings, and representations of the uncertainty associated with soil properties. The turbine support structure investigated is that promulgated by the National Renewable Energy Laboratory as typical of a monopile support structure designed for tens of meters of water depth and a characteristic wind/wave environment. We investigate the structural reliability using structural finite element models developed in MATLAB and a commonly used industry tool, FAST, developed and distributed by NREL.

Reliability investigations include the effect of spatial correlation of soil properties on reliability with respect to serviceability and the combined effects of loading and soil property uncertainty on structural performance. We also comment on the interaction between the tower/pile design space and the resulting reliability, allowing us to comment on the effect tower geometry may have on reliability.

FAST uses reduced order structural models in the pursuit of computational efficiency, and we evaluate the efficacy of these models for structural behaviors which may enter the nonlinear regime. These investigations include the ability of FAST to capture structural model shapes with large curvature gradients, and the effect of mode shape approximation on time-history dynamic analysis.

1 INTRODUCTION

In this paper we address some issues regarding uncertainty in the performance of monopile support structures for offshore wind turbines, a class of structures that are typically exposed to significant stochasticity during their operating lifetimes. Our attention is focussed on uncertainty in the soil properties and the ways in which geotechnical uncertainty propagates through the system to generate uncertainty in the structural response. The study is framed in the context of a reliability analysis of a typical offshore monopile support structure with respect to serviceability limit states on the mudline deflections and rotations. The main objectives of this paper are to define and illustrate an approach to uncertainty quantification for the soil-structure interaction of offshore monopile support structures and to provide a preliminary assessment of the importance of geotechnical uncertainty in driving overall performance reliability of the support structure. The need for such probabilistic analysis of OWT support structures has been emphasized recently by researchers, industry, and regulatory groups (Musial 2007, TRB–Transportation Research Board 2011).

OWT foundations pose an interesting design problem as they are subjected to random wind and wave loads and are situated in variable soil conditions that are difficult to characterize. Despite the amount of randomness inherent in the problem, OWT foundations are typically designed using a deterministic procedure with partial safety factors accounting for uncertainties in a general, non-site specific sense (similar to Load and Resistance Factor Design). The main OWT design standards and guidelines are Det Norske Veritas (DNV), Germanischer-Lloyd (GL), International Electrotechnical Commission (IEC) and most recently, American Bureau of Shipping (ABS). With the exception of IEC (which does not directly discuss reliability based structural design), all guidelines indicate that probabilistic methods may be appropriate for the design of novel and special cases (ABS-American Bureau of Shipping 2010, Veritas 2009, Commission 2009, WindEnergie 2005). In addition to this, DNV allows probabilistic analysis as a way of calibrating partial safety factors (Veritas 2009). If probabilistic methods are used, the guidelines do not provide further guidance and generally require special permissions.

The design guidelines separate limit states for OWTs into two main categories: ultimate and serviceability limit states in addition to fatigue. Ultimate limit states (ULS) describe the destructive failure of the OWT (such as yield or buckling), whereas serviceability limit states (SLS) refer to the limiting conditions under which the OWT can continue operating effectively. Several researchers have used probabilistic methods to analyze OWTs, summarized by Veldkamp (2006); however, the majority of these researchers were concerned with ULS and fatigue limit states, and more with loading uncertainty than geotechnical uncertainty (Veldkamp 2006).

The research presented here uses SLS and considers the effect of variable soil properties and random loading on OWT foundation reliability. SLS for monopiles are defined by specific mudline displacement and rotation limits that occur before pile ULS are reached and consequently are expected to be more sensitive to soil properties than the ULS of the support structure.

2 REFERENCE TURBINE CONFIGURATION AND PROBLEM STATEMENT

We use two separate test case offshore turbine designs in our study. The first is the pile design prepared by Lesny, Paikowsky, & Gurbuz (2007) for a 5MW turbine in the North Sea. This pile is made of steel with E = 200 GPA, and has a wall thickness of 0.07m, a diameter of 6m and an embedment depth of 38.9m. We use this reference pile primarily in our reliability studies of the serviceability limit state of the pile subject to geotechnically uncertain conditions.

For our investigation of the structural modeling capabilities of FAST, we adopt the National Renewable Energy Laboratory (NREL) 5MW on shore reference turbine as our test case. This turbine and associated support structure design has been developed to provide a realistic turbine/support structure pair that is freely available to the research community. The turbine is a composite of industrial 5MW turbines, heavily based on the REpower machine, has a base diameter and thickness of 6 and 0.027m, and a tower top diameter and thickness of 3.87 and 0.019m respectively. The tower is made of steel with E = 210 GPa and has a height above ground of 87.6m and a total mass of 350,000 kg. details on the NREL turbine are available in Jonkman, Butterfield, Musial, & Scott (2009)

Figure 1 shows the analysis model used to evaluate the soil-pile reliability. The applied forces at mudline are taken from (Lesny, Paikowsky, & Gurbuz 2007) and the response quantities of interest are the mudline lateral displacement and rotation. The soil resis-

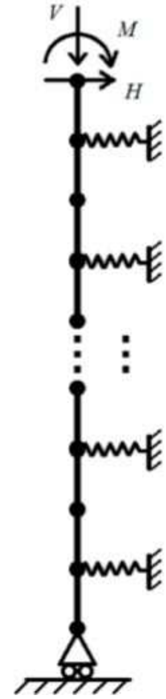

Figure 1: Reference pile model.

tance to pile displacement has been modeled using the API p-y method following industry standard practice. Details of the p-y curve approach and definitions are given in Institute (2005), and details of our particular model, which uses 20 discrete soil springs, are give in (Carswell 2012).

For the FAST simulations, the full turbine is modeled using standard FAST procedures which include, from a structural point of view, two mode shapes in each of the fore-aft and side-side directions. These mode shapes are used to perform a modal time history analysis of the turbine response to a stochastic wind field. We have attempted to test the robustness of FAST to changes in the structural mode shapes that may be brought on by structural yielding or damage by introducing stiffness reductions into the tower model at various locations and of varying degrees. We have examined the mode shapes that result from FAST (actually the ancillary package BModes) and a full finite element discretization, and have in turn evaluated whether a FAST time history analysis using the damaged mode shapes differs significantly from the time history analysis for the undamaged tower.

3 STOCHASTIC MODELS

3.1 *Soil property uncertainty*

The primary source of uncertainty that we consider in this study is that of the soil mechanical properties, and specifically we consider the friction angle ϕ'–we focus on sands–as the fundamental characteristic of the sands. Using empirical relations, all parameters of the API p-y curve model can be computed from ϕ' (Carswell 2012). In the design and analysis of an offshore structure the uncertainty associated with geotechnical conditions can stem from lack of information–

offshore site investigations are expensive– or from approximations and errors involved in the measurement of in situ soil properties. In this study we do not distinguish between the two as our primary interest is in assessing the degree to which geotechnical uncertainty propagates through to uncertainty in the structural response.

Letting the coordinate $x > 0$ represent the depth below the mudline, the stochastic friction angle is modeled as a one-dimensional stochastic field $\phi'(x)$. To adopt this model we neglect spatial variation of the material properties in the plane parallel to the seabed and perpendicular to the long axis of the pile, and we further assume that the pile is driven into a soil mass that is not bedded and therefore does not exhibit discontinuities in the friction angle with depth. We characterize the stochastic process $\phi'(x)$ by its marginal distribution $f_{\phi'}(\phi')$ and spatial auto-correlation function $R_{\phi'\phi'}(\tau)$, $\tau = |x_1 - x_2|$ and associated covariance $C_{\phi'\phi'}(\tau)$, $\tau = |x_1 - x_2|$ and scaled covariance $\rho_{\phi'\phi'}(\tau)$, $\tau = |x_1 - x_2|$ function. The friction angle process is assumed to be mean square stationary.

The friction angle ϕ' has physical bounds on the values it may take, and practical bounds that are substantially tighter then the theoretical physical bounds. We therefore adopt the beta distribution as a model for the marginal distribution of the friction angle and apply appropriate shift and scaling parameters such that

$$\phi'(x) = a_1 W + a_2 \tag{1}$$

$$W \sim \beta(A, B) \tag{2}$$

where the parameters $a_1 = 10$ and $a_2 = 30$ are chosen to give $\phi' \in [30^o, 40^o]$, a range that commonly occurs in subsea sands. Within this range of values, the parameters A and B provide a great deal of flexibility in selecting the shape, mean, and variance of the marginal distribution of the friction angle, and we will use this flexibility to conduct parameter and sensitivity studies.

Due to the very high spatial variability associated with subsea geotechnical conditions it is difficult to select appropriate parameters for the soil probability model with a specific site selected and site-specific characterizations. Nevertheless, the literature provides some guidance to our modeling effort. Phoon K-K ed. (2008) and Baecher & Christian (2003) divide sands into three categories of friction angle variability. For low variability sands the coefficient of variation is 0.5-0.10, for medium variability sands 0.10 - 0.15, and for high variability sands 0.15-0.20. Lacasse & Nadim (1996) report a COV for sand friction angle of between 0.02 and 0.05 based on laboratory tests, although much higher values have occasionally been reported (Sett & Jeremic 2009). Based on this information we have selected 0.05 as a typical coefficient of variation for our sands, and a typical accompanying mean value of $\mu_{\phi'} = 35^o$.

Again owing to the lack of a specific site and site characterization, we have elected to adopt two models for the spatial auto-correlation of the friction angle that should provide bounds on the response uncertainty. In one case the scaled covariance function is assumed to be $\rho_{\phi'\phi'}(\tau) = 1, \tau = 0, 0, \tau \neq 0$ and in the other $\rho_{\phi'\phi'}(\tau) = 1$. The first corresponds to a white noise process and the second to a process that, in our model, is spatially constant. The first represents an overestimate of the spatial uncertainty of the friction angle and the second an underestimate for practical situations. Figure 2 show samples drawn from each of the two models with $\mu_{\phi'} = 35$ and a COV of 0.05.

Although our primary interest is in geotechnical uncertainty, and we treat the loading as deterministic in most of this study, we adopt for some investigations a simple model for loading stochasticity in which the mudline bending moment and lateral force are treated as perfectly correlated random variables with a coefficient of variation of 0.05 and following a Weibull distribution.

Finally, the time history simulations we present that have used the FAST code assume a stochastic input wind field with a constant hub-height mean wind speed, wind shear profile, and stochasticity in time and space generated by wind field turbulence.

4 RELIABILITY STUDIES

We use a first order second moment approach to estimate the reliability of the offshore reference pile against the serviceability limit states of mudline lateral deflection and rotation, with limits on the deflection of 0.02m and on the rotation of 0.7 degrees so that the safety margin can be defined as

$$g(u, \alpha) = \min(0.2 - u, 0.7 - \alpha). \tag{3}$$

For this particular reference pile, the rotation limit dominates the behavior and the safety margin can be approximated by

$$g(u, \alpha) \approx 0.7 - \alpha. \tag{4}$$

The probability of failure and corresponding reliability are estimated for all cases shown in this paper by using Monte Carlo simulation to estimate the mean and variance, μ_g and σ_g^2 of the safety margin and then, assuming Gaussianity of the response, computing

$$\beta = \frac{\mu_g}{\sigma_g}. \tag{5}$$

In all cases 5000 MC samples were used to estimate the statistics of the safety margin.

4.1 *Baseline reliability study*

The baseline reliability study presented here evaluates the pile reliability for combinations of stochastic/deterministic soil properties (modeled with either

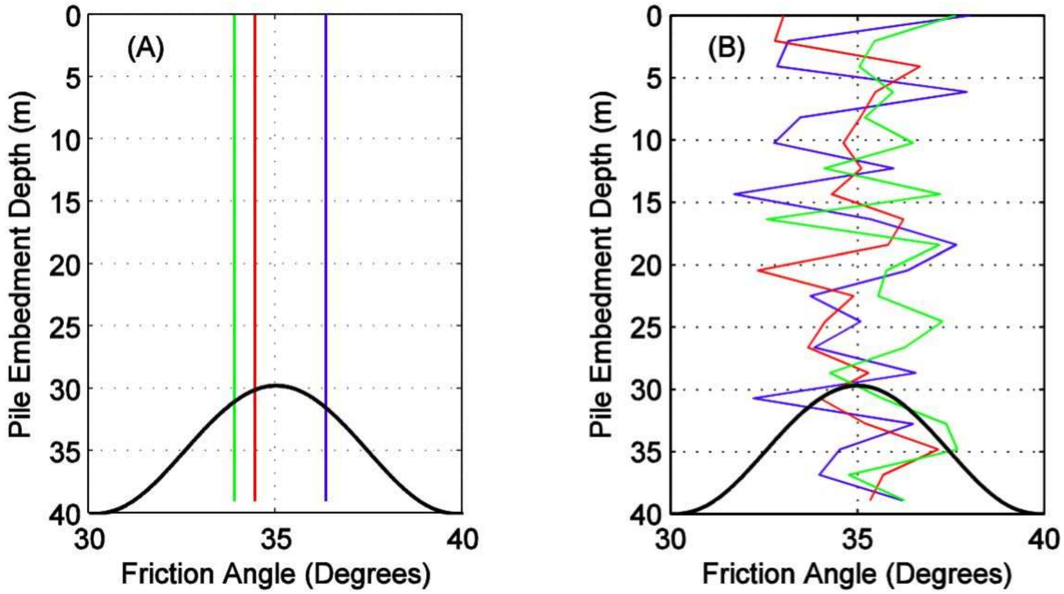

Figure 2: Samples of stochastic friction angle for (A) spatially constant friction angle and (B) white noise friction angle

Table 1: Baseline reliability study of reference pile for stochastic/deterministic load and soil properties. WN = white noise, RV = random variable meaning spatially homogeneous soil. Numbers in the table are the reliability index β.

	WN soil	RV soil	Det. soil
Stoch. load	3.0	2.8	4.1
Det. load	4.6	3.8	n/a

perfect spatial correlation (RV) or as a white noise process (WN)) and stochastic/deterministic loading. Summary results are given in Table 1 with a typical histogram and best fit Gaussian distribution to the mudline rotation shown in Fig. 3. We observe a substantial affect on the reliability of the degree of spatial correlation present in the soil property field when the loading is deterministic, with the white noise soil properties yielding a reliability index of 4.6 as compared with 3.8 for the case of spatially constant soil properties. When loading randomness is included in the analysis, the effect of soil property correlation is much smaller, with perfect spatial correlation lowering the reliability only from 3.0 to 2.8. The cases of deterministic soil / stochastic load and stochastic soil / deterministic load reveal that the effects of loading and soil property uncertainty are qualitatively similar, and that the correlation structure of the soil property field (RV v. WN) determines which source of uncertainty has a greater effect on pile response uncertainty. Note that the loading randomness modeled here (a COV of 0.05) is chosen to match the COV of the soil property uncertainty, and that loading and soil property uncertainties calibrated to match an actual site may result in qualitatively different results.

4.2 *Parameter studies*

We present in this section parameter studies intended to highlight the various ways in which variations in the magnitude and characteristics of the soil property uncertainty propagate through to uncertainty in the pile response. All results in this section are for the case of deterministic loading.

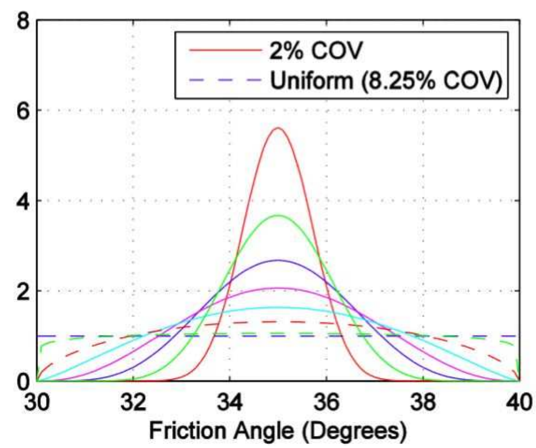

Figure 4: Family of beta distributions used in parameter study of soil property variance effect.

First, Fig. 4 shows a family of beta distributions for the friction angle marginal distribution with the same mean value but COVs ranging from 0.02 to 0.0825, with the latter corresponding to the uniform distribution. Figure 5 in turn shows how each of these beta distributions leads to different values for the reliability both for the case of white noise soil properties and spatially homogeneous soil properties. Given that reasonable models for soil property uncertainty use COVs of upwards of 0.02, the figure makes clear that the pile reliability is highly sensitive to the magnitude of soil property uncertainty and that therefore high quality site investigations could play an important role in improving reliability or allowing for more efficient design.

The second parameter study we conduct is on the effect of mean friction angle on the pile reliability. Figures 6 and 7 show, respectively, a family of beta distributions with consistent coefficient of variation of 0.05 and mean friction angle varying from 31.9^o to 36.6^o, and the resulting pile reliabilities. Note that

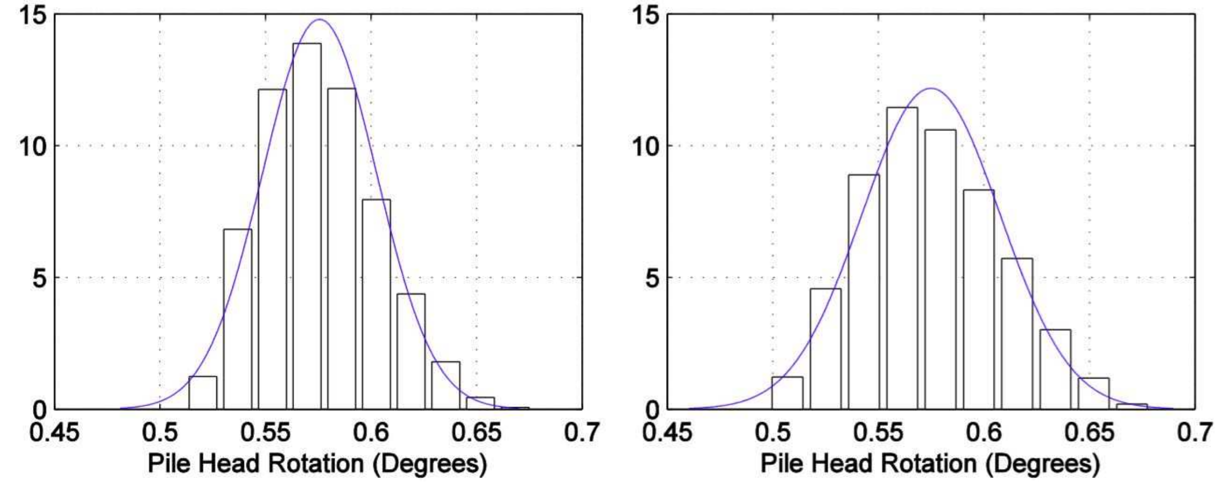

Figure 3: Mudline rotation histograms and best fit Gaussian distributions for the cases of (left) white noise soil properties and (right) spatially homogeneous soil properties.

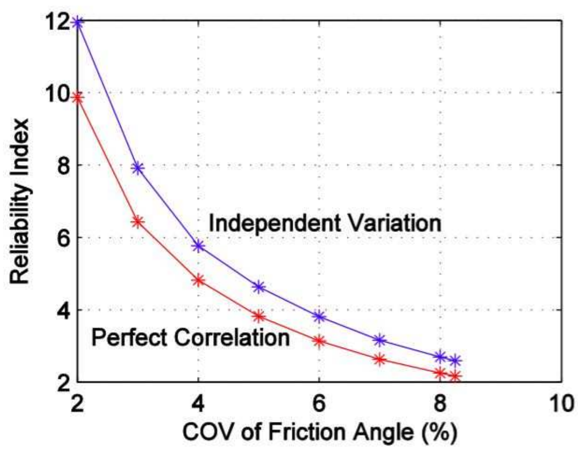

Figure 5: Effect of soil property variance on pile reliability.

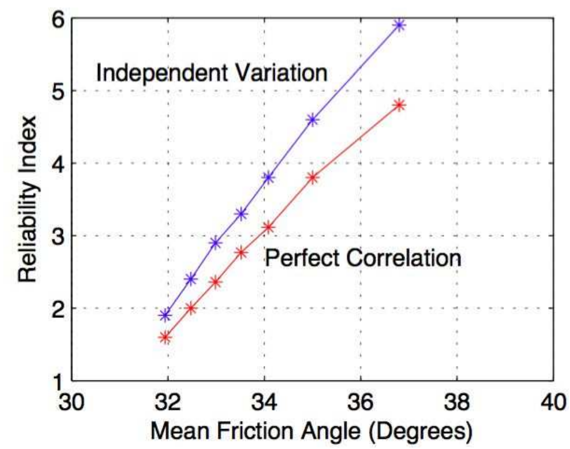

Figure 7: Effect of mean soil property on pile reliability.

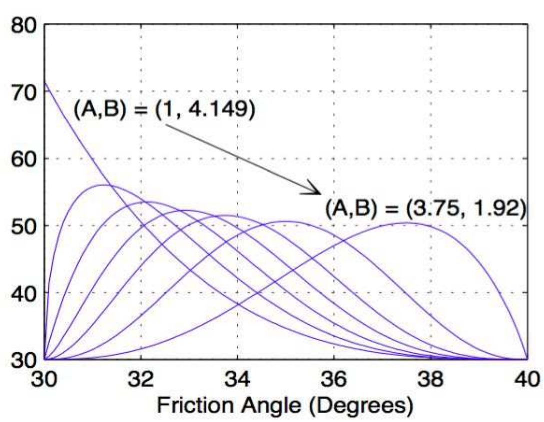

Figure 6: Family of beta distributions used in parameter study of mean soil property effect.

although the coefficient of variation is held constant the variance therefore increases for the distributions with higher mean friction angle. Despite the increasing variance of the distributions with larger mean friction angle, the overall effect is that of a large sensitivity of the reliability to even small increases in the mean friction angle. This points to the importance of accurately measuring the friction angle at a potential site and the possibility of dramatically improving performance with respect to the serviceability limit state by finding and selecting sites with better quality soil conditions.

4.3 *Design considerations*

We close our discussion of pile reliability with treatment of the interaction between design considerations and reliability measures. Figure 8 shows the effect of pile embedment depth on reliability, and a clear convergence is observed as the embedment depth approaches 35 to 40m. This value corresponds closely with the actual design depth of 45m, which of course has been chosen with many other design considerations in mind such as ultimate limit states for the pile and soil mass. Nevertheless, the results show a certain consistency between the embedment depth chosen for classical, deterministic, design reasons, and the embedment depth beyond which no significant gains in the reliability can be obtained.

The primary design parameters for the pile are the embedment depth–addressed in the previous paragraph–and the pile diameter and wall thickness. For a laterally loaded pile the moment of inertia–a combination of the wall thickness and diameter–largely governs behavior, but due to the dependence of the soil p-y curves on pile diameter the overall lateral stiffness of the soil-pile system does not depend solely on the pile moment of inertia, but potentially depends independently on the pile diameter and wall thickness. Figure 9 shows contours in the diameter-

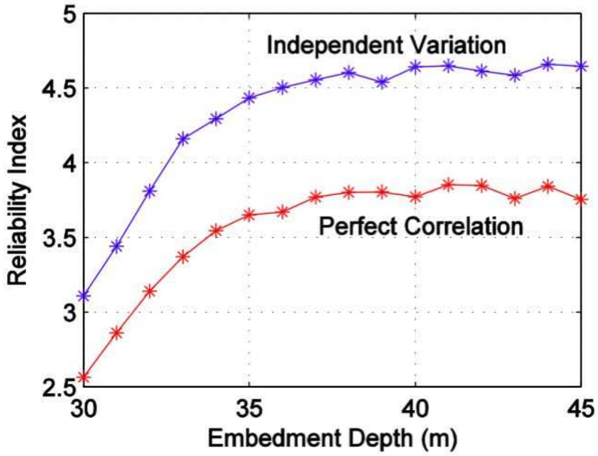

Figure 8: Effect of embedment depth on pile reliability.

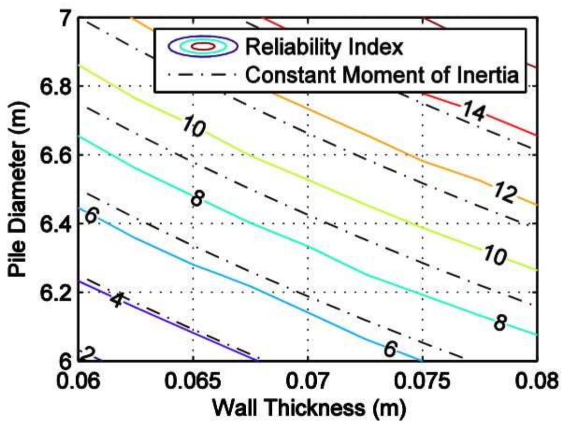

Figure 9: Effect of pile diameter and wall thickness at fixed moment of inertia on pile reliability.

thickness space for the pile moment of inertia and the reliability. The contour lines are essentially parallel to one another, meaning that in practice the dependence of the reliability on the specific choice of wall thickness and pile diameter is vanishingly small, and designers are free to choose a combination of wall thickness and pile diameter to meet other design requirements without affecting the reliability to any meaningful degree. The figure shows results only for white noise soil properties since the results were qualitatively similar for spatially homogeneous soil properties.

5 STRUCTURAL MODELING IN FAST

In this final section of the paper we address some issues regarding structural modeling in the wind turbine modeling software FAST. As described above, our interest is in the degree to which FAST, which uses modal analysis including two fore-aft and two side-side mode shapes for time history analysis of the support structure, can adequately represent the response of the support structure should material nonlinearity or structural damage occur. We consider the fixed bottom on-shore NREL reference turbine, and investigate the response when the bending stiffness at the base of the tower is reduced by factors of 0.50 and 0.90 over the length of one finite element–one

Table 2: Summary statistics for tower top displacement time history for damaged and undamaged towers

Tower state	Mean	Max	Std
Undamaged	020	0.39	0.048
0.50 damage	0.23	0.43	0.054
0.90 damage	0.25	0.46	0.059

twentieth of the tower height. These stiffness reductions can be thought of in a variety of ways with respect to the actual turbine performance: partial cross section yielding brought on by overload; partial or highly localized wall buckling brought on by overload; partial soil failure reducing the support stiffness. Furthermore, since at the present time modeling of multi-member support structures such as jackets must be accomplished in FAST by defining an equivalent monopole stiffness, the stiffness reductions we introduce can be abstracted one level further to correspond to damage near the base of a more complicated support structure type. Despite these connections to actual structural performance, this study is rather abstract, and is intended mainly to elucidate the ways in which FAST's structural modeling abilities compare to those that are present in most commonly used structural analysis softwares.

To use FAST for analysis, one must first, externally, compute the first and second fore-aft and side-side modes. These are then specified in the form of best fit polynomials, in the FAST input file. Figure 10 shows the first and second fore-aft mode shapes for the damaged and undamaged states of the tower. The damaged mode shape, as expected, has something approaching a slope discontinuity at the base due to the dramatic stiffness reduction.

Figure 11 in turn shows how the tower top displacement depends on the state of damage at the tower base. One can detect a meaningful difference in the displacement time histories, with the damaged tower exhibiting larger displacements, and the summary statistics of Table 2 show that not only is the mean displacement shifted upward but the variance of the displacement response increases substantially even at the lower damage level of 0.50. In summary, FAST appears able to represent the response of a damaged turbine tower. Due to the details of its operation, however, FAST is unable to update structural mode shapes on a timestep by timestep basis, and since the effect of tower damage on response is substantial, either the mode shapes would have to be updated manually at all time steps where damage evolves, or another analysis approach would have to be used.

6 CONCLUSIONS

This paper summarizes investigations into the reliability of offshore wind turbine soil-pile systems against excessive displacement and presents a discussion of the structural modeling capabilities of the widely used wind turbine analysis software FAST.

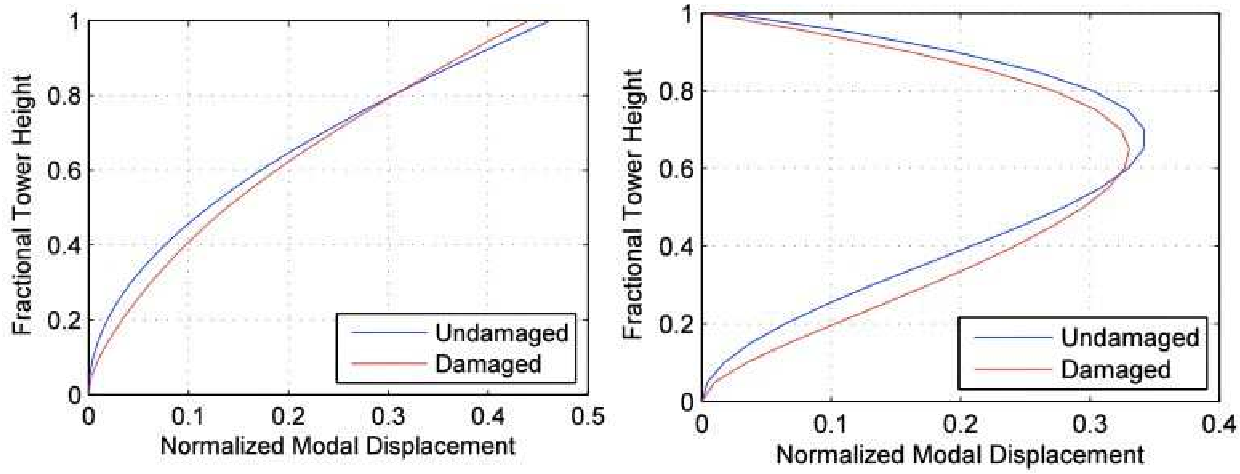

Figure 10: First and second fore-aft tower mode shapes with and without 0.90 damage at the base.

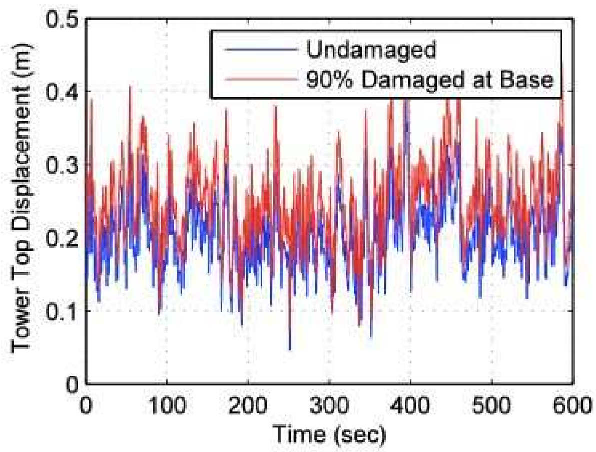

Figure 11: Tower top displacement time history for undamaged and 0.90 damaged towers.

Uncertainty in soil properties and loading appear to propagate in qualitatively similar ways through the soil-pile system into effects on the overall reliability. Choice of distribution model for uncertain soil properties is generates very large sensitivity in the resulting reliabilities, and those reliabilities are also highly sensitive to the mean and variance of the input soil properties, which in this study are determined by the friction angle. These results point to the need for high quality site investigations that can reduce geotechnical uncertainty and the importance of choosing sites with favorable geotechnical conditions to ensure high serviceability reliability.

With respect to structural modeling in FAST, we find that tower damage and associated stiffness reduction can dramatically alter tower response, and that therefore, if such damage may occur during extreme loading events being modeled by FAST, the analyst must take care either to conscientiously update structural mode shapes or use software with greater structural modeling capabilities.

7 ACKNOWLEDGEMENTS

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