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RELIABILITY-BASED DESIGN OF OFFSHORE WIND TURBINES EXPOSED TO HURRICANE RISK

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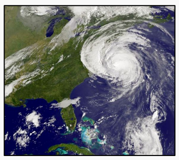
Introduction

- Current international standards for the design of offshore wind turbines do not explicitly consider loading under hurricane-induced wind and wave.
- These standards are sufficient for the design of offshore wind turbines installed along the European coast, a region that is not at risk to hurricanes, however, the legitimacy of applying these standards to turbines installed along the United States Atlantic and Gulf coasts, a region at considerable risk to hurricanes, has been recently questioned.

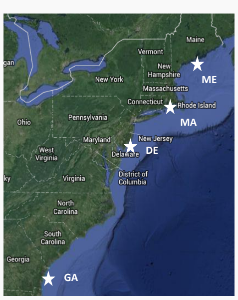


- It is widely agreed that variability in extreme loads is greater in areas exposed to hurricane risk. Therefore, it is expected that design standards for offshore structures in such areas should prescribe different load factors if a uniform structural reliability is to be achieved at all locations.
- In this project, we consider four locations along the U.S. Atlantic Coast and, for each location, design monopiles supporting the NREL 5MW offshore turbine. Designs are based on one of two methods for factoring extreme environmental loads. The first uses a load factor of 1.35, as recommended by the design standard IEC 61400-3, and, the second uses a load factor calculated based on the ratio between the unfactored mudline moment for design-level environmental conditions (50-year) and the same quantity calculated for more extreme conditions (500-year). The latter method is prescribed in API RP-2A 22nd edition for medium consequence offshore structures and is termed the 'Robustness Requirement.'
- The impact of these two methods is assessed by comparing material tonnage of monopiles designed with each method.

Site Information

Monopiles are designed for four sites along the U.S. Atlantic Coast. -- see below. The metocoean hazard data for three of the sites (ME, DE, and GA) are determined from multiple decades of buoy measurements by NOAA. All metocean hazard data includes measurements during hurricanes or tropical storms. The hazard data for the 4th site (MA) are obtained from MMI (2009).

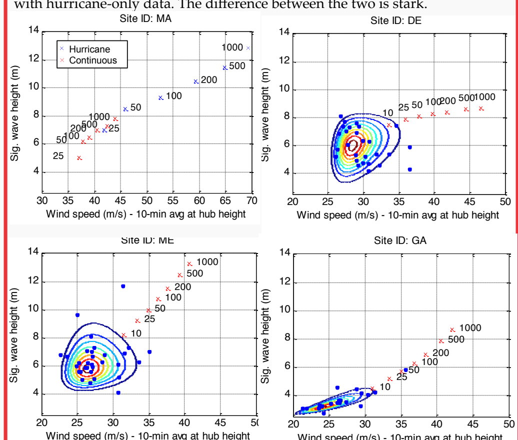
Site ID	Nearest State	NOAA Buoy ID	Water Depth (m)	Duration (years)
MA	Massachusetts	N/A	15.0	20
DE	Delaware	44009	30.5	29
ME	Maine	44007	23.7	31
GA	Georgia	41008	19.5	21



The MMI report (2009) did not provide sufficient data to estimate the joint distribution of annual wind and wave for the MA site. Rather, the report provided pairs of annual maxima of wind and wave for several mean return periods. The MMI report provides two sets of hazard data. The first is labeled 'continuous' and is based on 20-years of continuous measurements and is directly comparable with the NOAA data. The second is labeled 'hurricane' and is based on the past 100 years of hurricane activity without consideration of non-hurricane activity. This view of the hazard is markedly different than the continuous view.

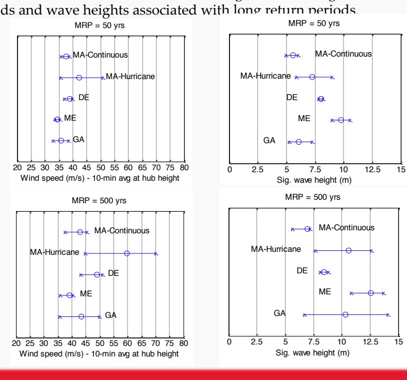
Metocean Hazard

For each of the three NOAA buoy sites, we have collected annual maxima of the significant wave height and wind speed. The figures below show contours of the best fit joint Generalized Extreme Value distribution along with a scatter plot of the actual data. The 'X' marks indicate the locations of the wind speed and wave height pairs at mean return periods from 10 to 1,000 years. The figures highlight the site-specificity of the hazard. It is particularly interesting to note that for the DE site, the wind speed increases much more than the wave height for long MRPs whereas for the other sites the increase is either essentially proportional (ME) or the increase in wave height appears to dominate (GA). For the MA site, red 'X' marks correspond to hazard assessed with continuous data while blue 'X' marks correspond to hazard assessed with hurricane-only data. The difference between the two is stark.

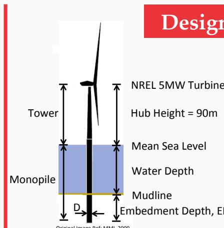


Data Duration & Hazard Sensitivity

Estimating the value of the wind speed and significant wave height corresponding to long return periods presents significant challenges when limited data are available. The figures below illustrate the uncertainty associated with estimates of the wind speed and significant wave height at 50 and 500 year mean return periods for the four sites. For each site and data source a generalized extreme value distribution has been fit to the collected data. Subsequently, a number of samples have been drawn from this best fit distribution equivalent to the number of data points in the original data set. This sampling procedure was repeated 20 times, and each time a new GEV distribution was fit. By extracting the wind and wave values for the 50 and 500 year MRPs for each of the 20 sets of realizations we are able to quantify the uncertainty associated with our estimates of the 50 and 500 year wind and wave conditions. In the figures, the open circles represent the mean of the 20 MRP values obtained and the X marks indicate the 25th and 75th percentiles of the simulations. The overlap between the 25%-75% intervals across the sites is indicative of the challenge of estimating the values of wind speeds and wave heights associated with long return periods.



Design Methodology



We design a monopile supporting the NREL 5 MW turbine for the four considered sites based on (1) the IEC load factor for extreme environmental loads (1.35) and (2) the API Robustness Requirement. The design space considers the monopile diameter D, the monopile thickness t and the monopile embedment depth, ED. The selected design is the lightest monopile which satisfies the following three conditions:

1. Resonance Avoidance. The natural frequency of the turbine, tower, monopile and elastic foundation is no closer than 10% away from the operational frequency boundaries defining the soft-stiff regime (i.e. between the 1P and 3P operational frequencies, 0.20 and 0.33 Hz)
2. Bending. The bending strength of the monopile, calculated per ISO 19902, is greater than the factored mudline moment under extreme environmental conditions.
3. Serviceability. Serviceability of the monopile has been assessed using a nonlinear p-y Winkler spring type model to compute the deformation f the soil-pile system under mudline moment, shear, and axial loading. All sites have been assumed to have similar soil conditions. The mudline rotation of the pile has been checked against a serviceability limit of 0.25 degrees, which corresponds to the additional rotation permitted to occur by the manufacturer of the turbine.

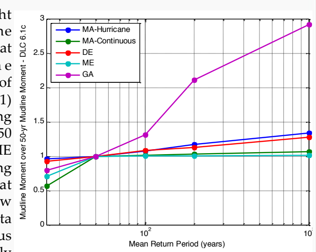
Mudline moments under extreme environmental conditions are calculated based on two IEC 61400-3 design load cases: 6.1b (extreme wind model + reduced wave height) and 6.1c (reduced wind model and extreme wave height). Waves are modeled nonlinearly with stream function wave theory and hydrodynamic loads are calculated based on Morison's equation. Breaking wave forces are calculated based on the Wienke model. All loads are calculated based on a static model of the turbine and monopile. Structural dynamics are considered by amplifying nonbreaking wave loads based on the ratio of the wave period to the structural period and by de-amplifying breaking wave loads based on the ratio of the structural period to the breaking wave duration.

Results

The designs for each of the four sites are provided in the table below. All designs, with the exception of the ME site which had especially severe wave loading, are controlled by resonance avoidance and, for these sites, there is no difference between the designs with different load factors.

Site ID	Design – Load Factor = 1.35				Design – Load Factor = Robustness Requirement			
	D (m)	t (m)	ED (m)	Mass (kg)	D (m)	t (m)	ED (m)	Mass (kg)
MA-Hurricane	5.5	0.04	25	9.3e5	5.5	0.04	25	9.3e5
MA-Continuous	5.5	0.04	25	9.3e5	5.5	0.04	25	9.3e5
DE	7.0	0.04	25	1.1e6	7.0	0.04	25	1.1e6
ME	7.5	0.08	35	1.6e6	7.0	0.06	30	1.3e6
GA	6.0	0.04	25	9.8e6	6.0	0.04	25	9.8e6

The figure on the right shows the ratio of the mudline moment ratio at several MRPs. The surprisingly small values of the ratio are a result of (1) breaking waves occurring more frequently than 50 years at the MA and ME sites, thus greatly limiting the increase in loads at longer MRPs and (2) low variability in hazard data calculated from continuous compared to hurricane-only data.



Acknowledgements

- **National Science Foundation**. Grants CMMI-1234560 and -12345656
- **Matt McLachlan**, Undergraduate Researcher at Northeastern.
- **Spencer Hallowell**, Graduate Researcher at Northeastern.
- **Vahid Valamanesh**, Graduate Researcher at Northeastern.
- **Wystan Carswell**, Graduate researcher at Umass
- **Rudolph A. Hall**, Keystone Engineering Inc.

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