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Providence, RI SRNL-STI-2013-00611

Reliability Based Design of Fixed Foundation Wind Turbines

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Abstract

Recent analysis of offshore wind turbine foundations using both applicable API and IEC standards show that the total load demand from wind and waves is greatest in wave driven storms. Further, analysis of overturning moment loads (OTM) reveal that impact forces exerted by breaking waves are the largest contributor to OTM in big storms at wind speeds above the operating range of 25 m/s. Currently, no codes or standards for offshore wind power generators have been adopted by the Bureau of Ocean Energy Management Regulation and Enforcement (BOEMRE) for use on the Outer Continental Shelf (OCS).

Current design methods based on allowable stress design (ASD) incorporate the uncertainty in the variation of loads transferred to the foundation and geotechnical capacity of the soil and rock to support the loads is incorporated into a factor of safety. Sources of uncertainty include spatial and temporal variation of engineering properties, reliability of property measurements applicability and sufficiency of sampling and testing methods, modeling errors, and variability of estimated load predictions. In ASD these sources of variability are generally given qualitative rather than quantitative consideration. The IEC 61400-3 design standard for offshore wind turbines is based on ASD methods.

Load and resistance factor design (LRFD) methods are being increasingly used in the design of structures. Uncertainties such as those listed above can be included quantitatively into the LRFD process. In LRFD load factors and resistance factors are statistically based. This type of analysis recognizes that there is always some probability of failure and enables the probability of failure to be quantified. This paper presents an integrated approach consisting of field observations and numerical simulation to establish the distribution of loads from breaking waves to support the LRFD of fixed offshore foundations.

Introduction

Forty-two percent of the offshore wind resource in U.S. waters of the Atlantic Ocean is in shallow water, with the remaining amount split evenly between intermediate and deep water, Figure 1. Offshore wind farms in areas prone to hurricanes and in shallow water may experience steep and breaking waves. Breaking and steep waves can be the dominant load that a wind turbine sees over its design lifetime, but little is known about their characteristics. Existing equations for forces from waves (i.e., the Morrison equation) may not be applicable in these conditions with large diameter monopile and gravity foundations. Recent analysis of offshore wind turbine foundations using both applicable API and IEC standards show that the total load demand from wind and waves is greatest in wave driven storms. Analysis of overturning moment loads (OTM) reveal that impact forces exerted by breaking waves are the largest contributor to OTM in big storms at wind speeds above the operating range of 25 m/s.

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Currently no codes or standards for offshore wind power generators have been adopted by the Bureau of Ocean Energy Management Regulation and Enforcement for use in the hurricane-prone shallow waters of the Outer Continental Shelf off the United States.

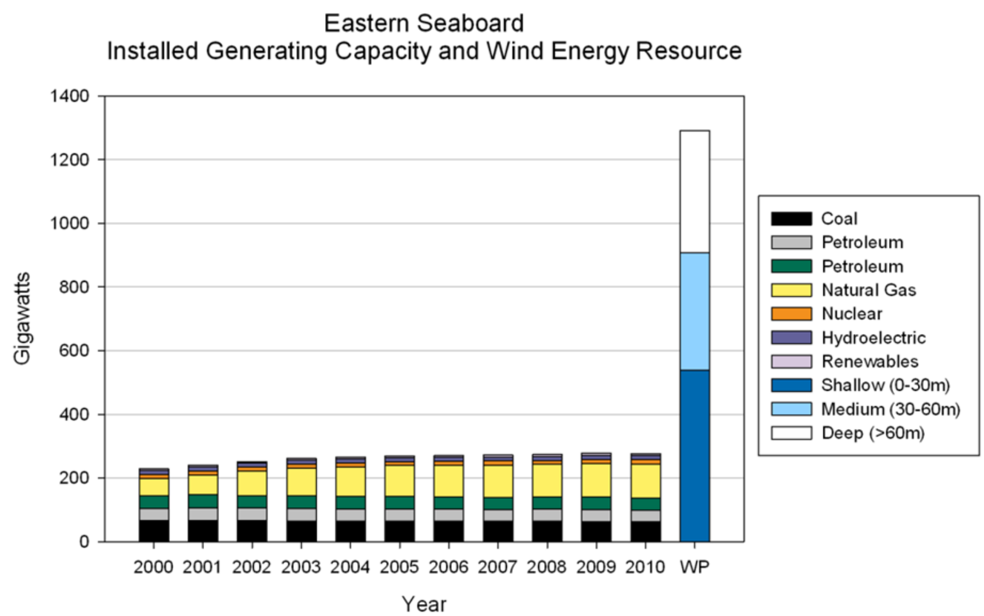

Figure 1 Installed generating capacity by fuel and wind energy resource for Eastern Seaboard by water depth within 50 nautical miles of the coast.

Allowable stress design (ASD) incorporates the uncertainty in the variation of loads transferred to the foundation and geotechnical capacity of the soil and rock to support the loads into a factor of safety. Sources of uncertainty include spatial and temporal variation of engineering properties, reliability of property measurements applicability and sufficiency of sampling and testing methods, modeling errors, and variability of estimated load predictions. In ASD these sources of variability are generally given qualitative rather than quantitative consideration. The IEC 61400-3 design standard for offshore wind turbines is based on ASD methods. Load and resistance factor design (LRFD) methods are being increasingly used in the design of structures. Uncertainties such as those listed above can be included quantitatively into the LRFD process. In LRFD load factors and resistance factors are statistically based, Figure 2. This type of analysis recognizes that there is always some probability of failure and enables the probability of failure to be quantified.

The goal of the work in this project is to develop an integrated approach consisting of field observations and numerical simulation to establish the statistical distribution of loads from breaking waves to support the LRFD of fixed offshore foundations. A dynamically coupled met-ocean modeling system (DcRWS-metocean model) was assembled using the Earth System Modeling Framework system of public domain software consisting of the Weather Research and Forecasting (WRF) model, Regional Ocean Modeling System (ROMS), and the Simulated Waves Nearshore Shallow Water Waves model (SWAN) to analyze the spatial and temporal variability of breaking waves.

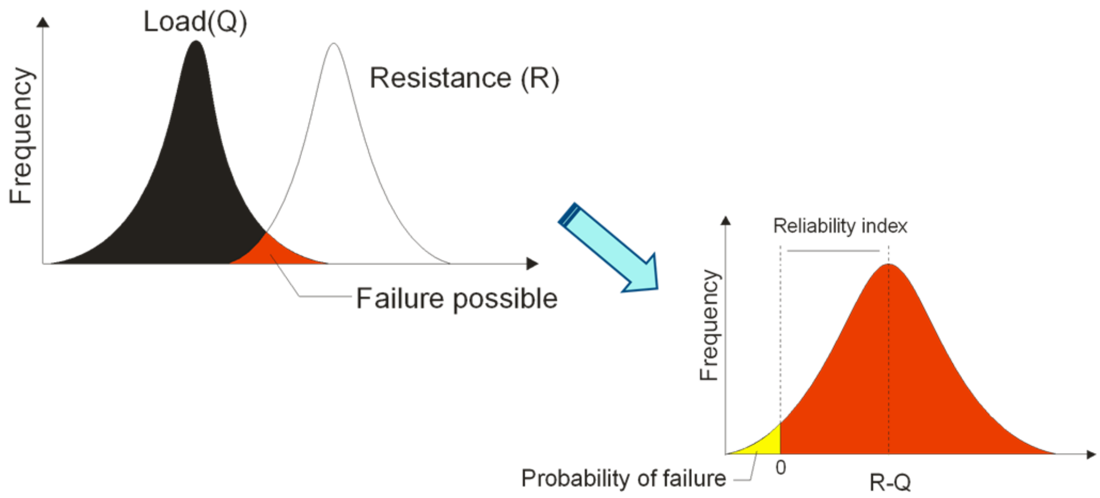

Figure 2 Probability of failure determined from statistical analysis of loads and resistance.

Methods

Geographic information system (GIS) tools and simulation results can be integrated to assess and map the spatial and temporal variability of parameters and indices related to breaking waves as wave steepness and the International Electrotechnical Commission (IEC) 61400-03 breaking wave parameter. Use of temporal data from the DcRWS model will enable the statistical analysis of breaking wave conditions and generation of inputs for reliability based design of offshore wind turbine foundations. Modeling and mapping results were used to identify a site for deployment of a research buoy to collect data to verify breaking wave modeling and test a new technology for identifying breaking waves. The buoy is equipped to measure many ocean parameters related to waves, currents and tides aw wells as meteorological data. A bottom mounted upward looking Acoustic Doppler Profiler (ADP) is being used to measure the directional wave spectra and the water current; which can affect the shape of the waves. A vertical beam from the ADP will track the sea surface and provide time series of the sea surface height. From this, the slope of the sea surface can be inferred and breaking waves identified. At times, a diagnostics mode will be used to measure the echo intensity within the water column to identify potential entrained air that may be a signature of breaking waves.

Computational fluid dynamics (CFD) modeling is being used to simulate breaking wave loads on a monopile to analyze time variation of horizontal and vertical forces and associated moments in water depths where breaking waves are anticipated. The CFD model uses a numerical representation multi-phase flow in a wave tank with a flap-type wave generator to create simulated waves to analyze slam forces on a hypothetical monopole foundation installed at the test site. The model contains a s lope on the bottom to represent a structure on the ocean floor at the test site.

Computational fluid dynamics (CFD) modeling is being used to simulate breaking wave loads on a monopile to analyze time variation of horizontal and vertical forces and associated moments in water depths where breakers are anticipated. The CFD model uses a numerical representation of a wave tank with a flap-type wave generator to create virtual breaking waves to analyze slam forces on a hypothetical monopole foundation installed at the test site. Waves created by the flap propagate across the model over the slope.

Adjusting the speed of the flap varies the wave length, wave period, wave height and wave celerity. Field data from the test site will be used to calibrate the CFD model of waves.Field data from the test site will be used to calibrate the CFD model of waves.

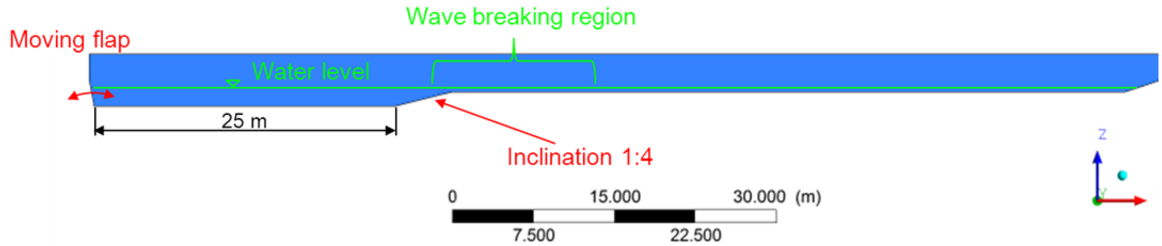

Figure 3 Schematic of CFD model for studying breaking waves.

Results

A research buoy equipped with an extensive suite of monitoring equipment for studying the test site was deployed off the coast of South Carolina in August 2013, Figure 4. The DcRWS was used to assess the variability of significant wave height at selected locations during Hurricane Sandy, Figure 5.

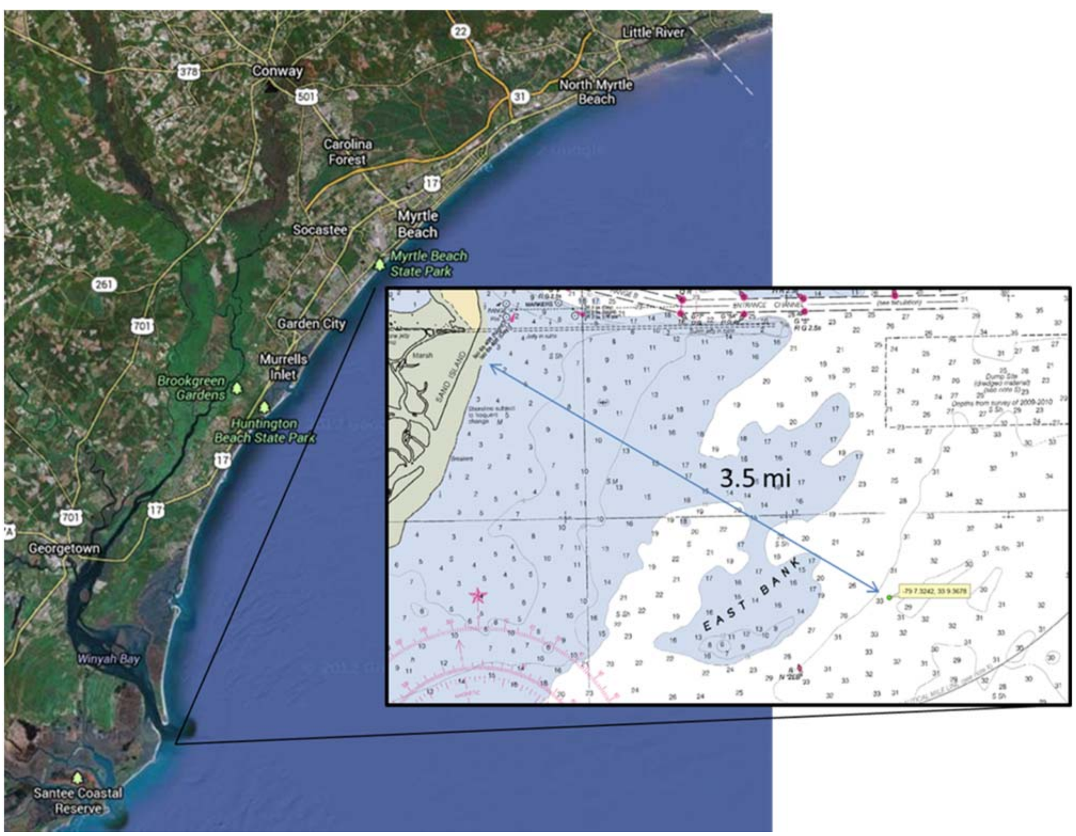

Figure 4 Location of test site and buoy deployment.

The temporal development of significant wave height during the timeframe surrounding Hurricane Sandy is shown in Figure 5. Probability distribution functions for significant wave height were also prepared. The PDFs can be combined with information on water depth to determine the frequency of conditions conducive to breaking waves.

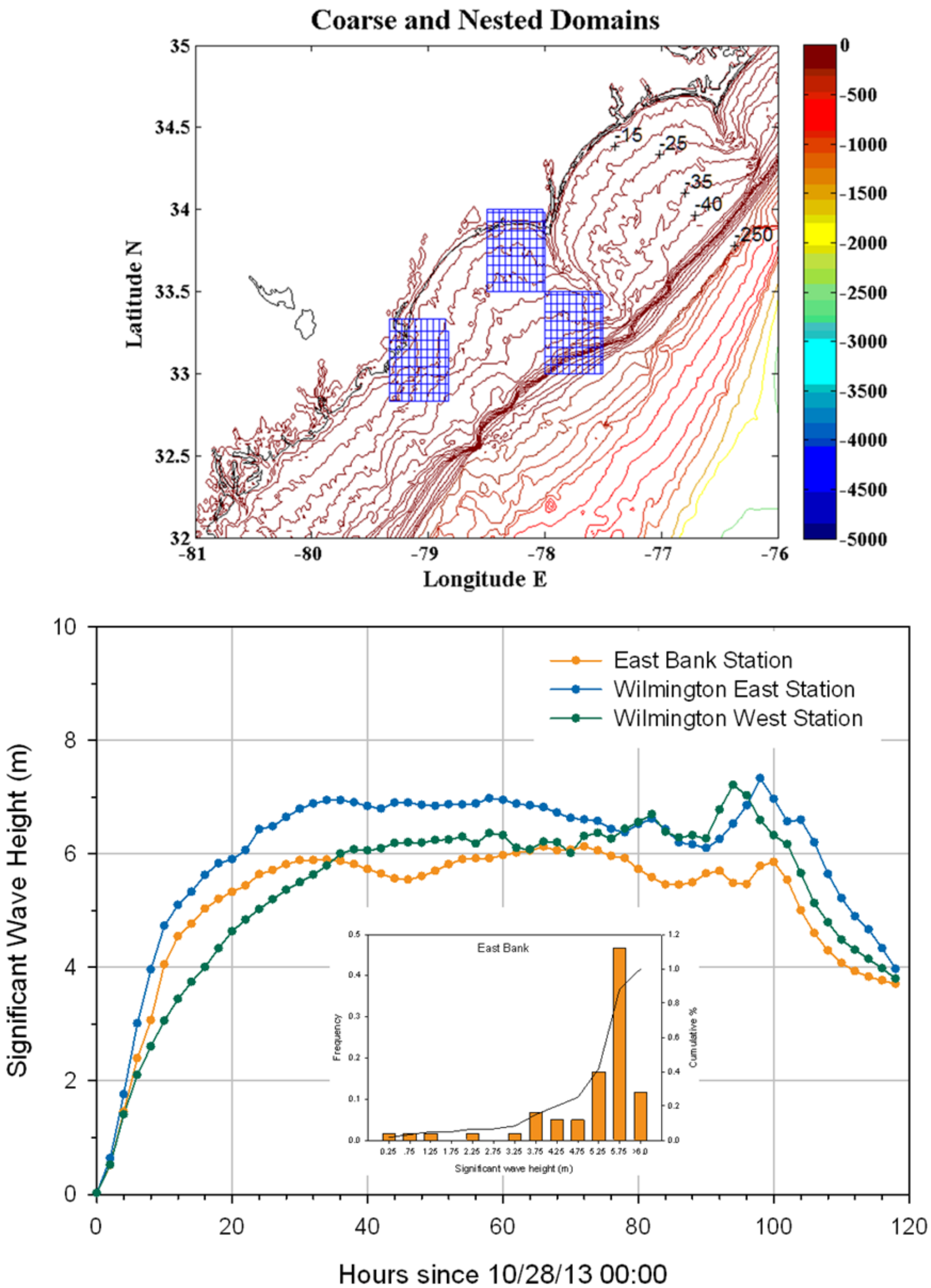

Figure 5 Results from DcRWS simulation of Hurricane Sandy.

Two dimensional CFD was used to simulate breaking waves, Figure 6. Breaking waves are indicated when the liquid phase fraction is significantly less than one during entrained air in the wave from breaking. During this initial phase of simulation it was discovered that the amount of water-air interface drag influences the breaking point. This observation will be further investigated. A 3D CFD model is being developed for the site test site and will be validated with field data. In the next stage of the project the 3D model will be used to estimate the hydrodynamic forces from steep and breaking waves on monopile foundations.

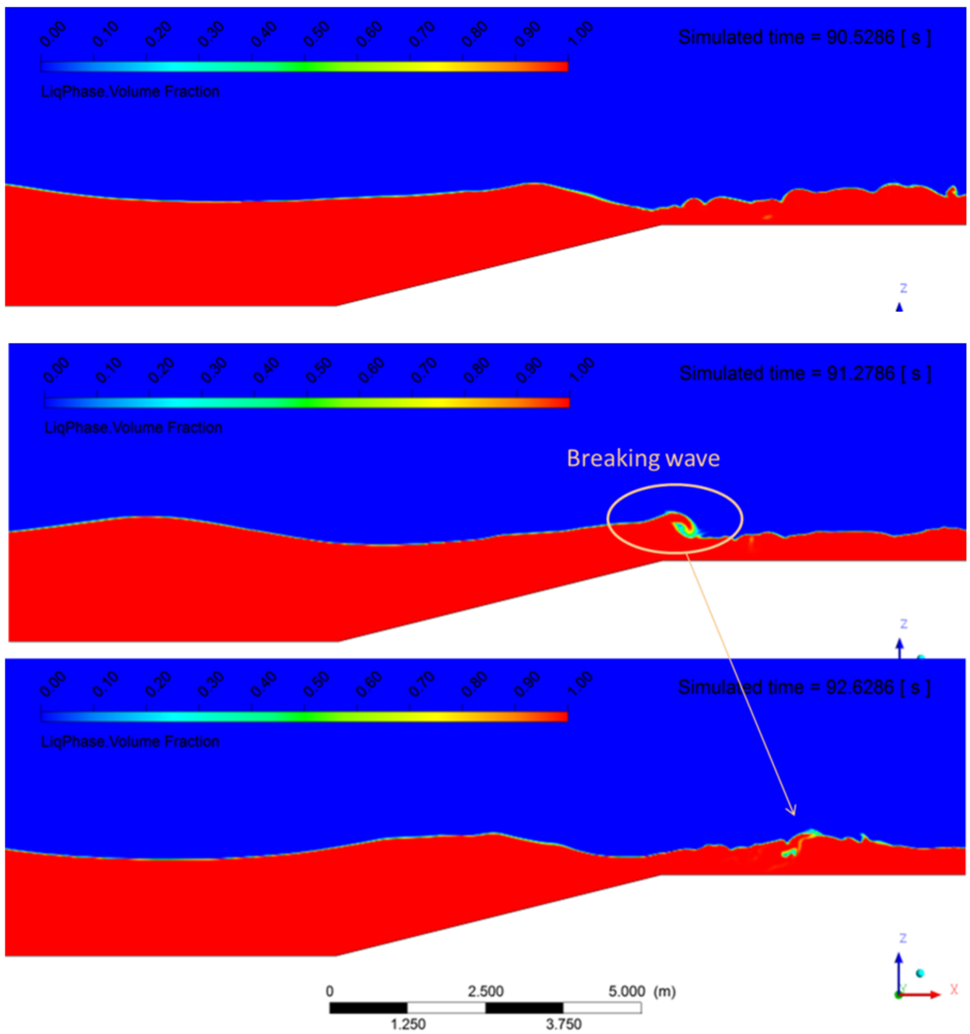

Figure 6 Results from 2 dimensional CFD modeling of breaking waves.

Acknowledgments

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