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Strength, stiffness, resonance and the design of offshore wind turbine monopiles

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ABSTRACT

A monopile supporting an offshore wind turbine (OWT) is currently designed for both strength and stiffness. Regarding strength, the monopile is designed to have sufficient capacity to withstand demands under both 50-year operational conditions, when the rotor is spinning and blades are oriented to optimize power generation, and 50-year extreme conditions, when the rotor is parked and the blades feathered to minimize aerodynamic loads. Regarding stiffness, the monopile is designed to have sufficient stiffness such that the first structural frequency of the OWT falls between the 1P and 3P frequencies (rotation frequency and blade passing frequency for a three-bladed turbine). For six case studies, including three sites along the U.S. Atlantic coast and two mudline conditions (fixed and compliant), this paper delineates the conditions under which stiffness and strength govern the design of the monopile. This distinction has important implications for the overall risk profile of an OWT, as monopiles controlled by stiffness will have more reserve capacity than monopiles controlled by strength. The six case studies are intended to consider a range of water depths, metocean environments and mudline conditions that is representative of conditions suitable for installing OWTs supported by monopiles along the U.S. Atlantic coast. The monopile designs are controlled by stiffness for two of the six cases studies and, for these two cases, a modest (6–8%) reduction in monopile area (and mass) could be achieved if dynamic design requirements were achieved through means other than increasing monopile stiffness. Monopile designs for the remaining four cases are controlled by operational moment demands.

1. Introduction

This paper attempts to delineate the conditions under which resonance avoidance (i.e. stiffness) and strength govern the design of the offshore wind turbine (OWT) monopile, using an idealized utility scale 5 MW wind turbine as an example. Since the mass of a turbine is fixed and since the mass and stiffness of the support structure cannot be treated as independent design parameters, the resonance avoidance condition is satisfied primarily by designing the support structure stiffness such that the first structural frequency of the OWT is between the 1P and 3P frequencies (rotation frequency and blade passing frequency for a three-bladed turbine) [1], and preferably also significantly above the peak spectral content of the wind and wave loading frequencies. Although the character of the dominant design criterion is not particularly important for the specification-based design of the support structure, it has important implications for the overall risk profile of an OWT. For example, if the support structure design is driven by stiffness considerations, it may have significant reserve capacity at the design loads (typically related to the 50-year conditions) and therefore a substantially lower risk profile with respect to more extreme events than a similar structure controlled by strength considerations. While the overall risk profile of an OWT does not directly affect design, it does have meaningful implications for financing, underwriting, and regional and national scale energy security planning.

The support structure of an OWT extends from the bottom of the foundation, which is embedded below the mudline, to the hub of the turbine. Offshore, the design of the support structure takes on added importance because of the additional total structural height from mudline when compared with height above land for onshore turbines, the greater uncertainty in soil conditions [2,3], and the additional loading induced by the sea state particularly for extreme storms such as hurricanes. The complexity of the OWT structural system—soil conditions, foundation, support

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Nomenclature

1P	rotor frequency
3P	blade passing frequency for a three-bladed turbine
A	cross sectional area of monopile (m^2)
D	diameter of monopile (m)
$F_X(x)$	cumulative distribution function of random variable X evaluated at $X = x$
GEV	generalized extreme value distribution
H_s	significant wave height (m)
I	turbulence intensity
MRP	mean recurrence period (year)
OWT	offshore wind turbine
T_p	peak spectral period (s)
V	wind velocity, hourly at hub height, 90 m above mean sea level (m/s)
$f_{X(x)}$	probability density function of random variable X evaluated at $X = x$
f_{n1}	first natural frequency of structure (Hz)
g	gravitational acceleration (m/s^2)
t	thickness of monopile (m)
u_1, u_2	standard normal random variables
Φ	standard normal cumulative distribution function
β	radius of circle in standard normal space
κ	shape parameter of GEV distribution
μ	location parameter of GEV distribution
σ	scale parameter of GEV distribution

structure, hydrodynamic loads, operational loads, aerodynamic loads—means that a myriad of design load cases (DLCs) and design objectives must be considered. Loads must be evaluated for a large variety of conditions such as normal operational conditions, abnormal operational conditions (e.g. start-up, shut-down, or emergency shut-down) and extreme conditions during which the rotor is parked and the blades feathered. These conditions are considered through a suite of more than 20 DLCs specified in IEC 61400-3 [4]. The structure must be designed to have sufficient strength and fatigue life under these DLCs, but an additional requirement that differentiates the design of OWT support structures from traditional structures is that the first natural frequency of the OWT must be separated from the operational frequencies of the rotor to avoid resonance. Depending on site conditions, strength, fatigue lifetime, and resonance avoidance may all govern the final design of the support structure.

The most common support structure for OWTs is the monopile, a circular hollow steel tube that is embedded into the seabed and extends above sea level where it connects to the OWT tower. Roughly 66% of the 318 GW of worldwide offshore wind capacity installed as of late 2013 is generated by turbines supported by monopiles [5]. Most (63%) of this capacity is located in shallow water (water depth < 30 m) [5] where monopiles have been found to meet the structural requirements of IEC 61400-3 at lower cost than alternatives.

OWT support structures fall into a design category that sits between essentially public civil structures, governed by governmentally prescribed design codes, and electro-mechanical devices that are typically designed based on proprietary and market-driven criteria; consequently, there has been relatively little discussion in scholarly literature of the design drivers of OWT support structures, with much of the information regarding this issue being held as proprietary by OWT designers, manufacturers and developers. The conclusions of what has been published [6,7] is ambiguous regarding the relative importance of strength and stiffness in OWT support structure design, with perhaps some preponderance of the evidence favoring the importance of stiffness. If stiffness is indeed a design-driver for most monopiles, an obvious question is whether this situation allows for the most efficient development of the offshore wind resource or whether it would be preferable to avoid resonance through methods other than increasing stiffness (e.g. tuned mass dampers), thereby opening the potential for more efficient monopiles.

In an attempt to provide an answer to whether OWT monopile design is driven by resonance avoidance or strength considerations — putting aside fatigue life as a design driver — this paper takes the following approach:

(1) three sites are selected along the U.S. Atlantic coast that are amenable to offshore wind energy development and are representative of a range of geographical, oceanic, and meterological conditions appropriate for monopiles;
(2) a wind-wave hazard model is developed that uses buoy measurements to calculate operational and extreme wind and wave conditions at each site corresponding to the design (50-year) mean recurrence period (MRP);
(3) operational and extreme dynamic loads on the OWT along with natural frequencies are calculated for an extensive range of monopile diameters and wall thicknesses and for two types of mudline boundary conditions (fixed and compliant) for each of the three sites. Using these results, a determination is made as to whether stiffness or strength drives the design and what margin exists between the two;

The paper begins by providing details on the three offshore sites considered, including a description of the available measurements of wind and wave conditions at these sites. The next section describes the two methods employed for using measurements of wind and wave to calculate intensities for operational and extreme conditions at a MRP appropriate for design (50-years, per IEC 61400-3). In the following section, the structural model which is employed to convert wind and wave conditions to structural demands (i.e. load effects) is introduced and the method for selecting a monopile diameter and thickness which satisfies both strength and stiffness requirements for each site is described. Next, the numerical results for the wind and wave conditions and the monopile designs are provided for each site along with discussion of the results. The paper concludes with a summary of the findings.

2. Site descriptions

Three sites along the U.S. Atlantic coast are considered in this paper, selected based on a combination of geographic features and the availability of metocean data. Sites located along the mid-Atlantic and Northeastern coasts were favored because the majority of proposals for offshore wind energy development in the U.S. are located there. The three selected sites correspond to the location of metocean data buoys maintained by National Oceanic and Atmospheric Administration (NOAA) with at least 20 years of data available and where water depths are in the reasonable range for monopile support structures (15–30 m). Given these considerations, three sites have been selected that lie off the coasts of the states of Maine, Delaware, and Georgia (identified